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DISSERTATION

EVALUATION AND ASSESSMENT OF IN-PIPE INSPECTION ROBOTS FOR IMPROVEMENT OF OPEN INNOVATION EFFICIENCY IN ROBOT-BASED DEVELOPMENTS IN PETROLEUM INDUSTRY

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Doktors der technischen Wissenschaften unter der Leitung

von

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Kurzfassung

Zweck dieser Dissertation ist es, Roboter die für die Inspektion und Wartung von Pipelines eingesetzt werden zu analysieren, zu evaluieren und neue Ansätze in diesem Forschungsfeld zu schaffen. Ein weiteres Ziel besteht darin, ein Open Innovation Werkzeug aufzuzeigen, dass in der Lage ist komplexe autonome Lösungen aus dem Bereich der Erdölindustrie auf einer gewöhnlichen Online-Plattform anzubieten. Der Rahmen dieser Arbeit erlaubt es, technologische Innovationen im Bereich der Robotik im Einsatzgebiet der Erdölindustrie zu untersuchen und zu evaluieren. Der Fokus der Untersuchung liegt auf dem Antriebssystem von Robotersystemen die für die Wartung und Inspektion von Pipelines konstruiert wurden. Außerdem werden die damit verbundenen Variablen analysiert und Grenzen aufgezeigt um ein Entscheidungskriterium und damit einhergehend, einen effektiven und kosteneffizienten Leitfaden zu generieren, der den Anforderungen von autonomen Systemen unter den Gegebenheiten die in der Produktion und Exploration in der Ölindustrie gestellt werden, gerecht wird.

Innovationen sind in der Ölindustrie nicht öffentlich und kostenorientiert. Aus dieser Situation entsteht des Bedürfnis ein Werkzeug zu entwickeln, dass den Benutzer von Beginn des Innovationsprozesses bis hin zur komplexen Problemdefinition eines autonomen Systems in einer effektiven und effizienten Weise unterstützt. Andererseits ist die Ölindustrie sehr sensibel betreffend technologische Entwicklungen und sehr konservativ in Bezug auf Unternehmens- oder Forschungsgeheimnisse. Dies weckt das Bedürfnis einer akkuraten und definierten Überführung zu den angesprochenen Plattformen, um unter Zuhilfenahme eines passenden Modells eine Open Innovation Anwendung im Bereich der Inspektions- und Wartungsrobotik zu ermöglichen.

Der Kern der Arbeit bildet die Hochleistungsrobotik in der Ölindustrie, fokussiert auf Verbesserungen in der Wartung und Inspektion und analysiert existierende Antriebstechnologien anhand von Variablenklassifikationen. Von diesem Startpunkt werden eigene Parameter definiert und in der Klassifikation ergänzt. Danach werden Roboter anhand eines 5-Punkte Systems evaluiert um einen optimalen Entwicklungsüberblick zu schaffen. Bei der Evaluierung wird außerdem auf die unterschiedlichen Anforderungen der verschiedenen Industrie-Steakholder eingegangen und diese genauestens analysiert. Um die Lücke zwischen Stakeholder Anforderungen und den derzeitig existierenden Entwicklungen zu schließen, wird ein neuer „ball-rad“ Roboter als Designansatz für eine nachhaltige und robuste Inspektionsleistung vorgeschlagen.

Abstract

The purpose of this dissertation is to analyze and evaluate in-pipe inspection robots and to develop and offer an Open Innovation standardization tool to transform enormous researches of autonomous solutions of petroleum industry to a common platform. Framework of this dissertation allow to inspect and investigate main robot-based technological innovations of petroleum industry, more focused on in-pipe inspection robot's locomotion and developments, highlight the variables and evaluate constraints to create the assessment criteria, however is enough to create guidelines of effective, cost efficient and favorable evaluation and assessment tool to follow solutions which fulfills autonomous system needs in in-pipe inspection of petroleum exploration and production industry.

Since innovations in petroleum industry are closed and cost oriented, there is a need for a tool that can guide the innovator from beginning of problem definition to autonomous system development as a solution in an effective and efficient way. On the other hand, petroleum industry is a highly sensitive area for safety and security of technological development and conservative in terms of company or research secrets, which creates a need for accurate transmission of definitions to the intended platforms, to evaluate in a right way and transfer the evaluation to a relevant model, which can be used for Open Innovation application in robot-based solutions of petroleum industry.

This work introduces the petroleum robotics, focuses on improvements in in-pipe inspection robot developments and as a first phase of the main part evaluates existing locomotion technologies of chosen robots and evaluating them in variables point of view. From this starting point, own – parameters those are not well considered and explained in the literature will be defined deeper and added to criterion formation. Second phase is evaluation of whole development in 5–points system to give a better view of where the developments stand today. Later on, projects and methods will be presented and evaluated in 5-points evaluation method developed by this work. Furthermore, the evaluation of existing projects due to the requirements of all different stakeholders of the industry will be presented and evaluated, as well as the gaps in the field and further opportunities will be discussed, and the suggestions such as unification of the parameters in formation of Open Innovation approach in the industry and a new type of robot concept out of the evaluation, the ball-wheeled robot will be proposed for sustainable and robust inspections.

Description of Research Topic:

EVALUATION AND ASSESSMENT OF IN-PIPE INSPECTION ROBOTS FOR IMPROVEMENT OF OPEN INNOVATION EFFICIENCY IN ROBOT-BASED DEVELOPMENTS IN PETROLEUM INDUSTRY

It is commonly held belief that oil is main part of modern society and has a significant impact on industry, science, economy, politics, and daily life of human beings and cannot be entirely superseded by any substitute material, add to this, lifetime of oil cannot be certainly forecasted, therefore, situation does not allow an efficient exploration, production and management. While correct, the common-sense omits a second that a global and multilateral approach and innovations would allow utterly utilization of oil and comfortable transition to alternative goods. According to the World Bank reviews National Oil Companies (NOCs) control approximately 90 percent of the world’s oil reserves and 75 percent of production (similar numbers apply to gas), as well as many of the major oil and gas infrastructure systems. Since NOCs do not intend to share achievements and developments, efficiency of so called „Open Innovation“, in petroleum industry needs to be applied and improved.

In this work the research is focused on existing and potential technological developments and upcoming robot-based technology improvements in in-pipe inspection robots sector of petroleum industry. Therefore, the next step will be to evaluate the state of the art in development projects and existing technologies and in-use robots and classify the depending variables of the locomotion first time in this field, create evaluation method to scan the situation, highlight problems and developments as well as summarize opportunities and offer a new concept of in-pipe inspection robot.

Based on the results of defined variable evaluation, an assessment method with defined criteria will be applied as a new tool for improvement of Open Innovation efficiency in robot-based technological developments will be presented. After the evaluation of existing projects, a novel design and concept of a new type of inspection robot – ball-wheeled robot will be discussed and relevant suggestions will be made.

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List of Abbreviations

AERI: Alberta Energy Research Institute

AOST: Alberta Oil Sands Technology

AOSTRA: Alberta Oil and Sands Technology Research Institute

ATEX: Atmospheres and Explosives

BTU: British Thermal Units

CCD: Charge-Coupled Device

CMOS: Complementary Metal-Oxide-Semiconductor

DCAM: Diameter Change Adaptation Mechanism

DOF: Degrees of Freedom

EoL: End of Life

FINEP: Funding Authority for Studies and Projects

GPS: Geometrical Product Specifications

HSE: Health, Safety and Environment

IMU: Inertial Measurement Unit

IPC: International Pipeline Conference

ISV: Independent Software Vendor

LED: Light-emitting Diode

LNG: Liquefied Natural Gas

LPG: Liquefied Petroleum Gas

MCP: Manual Control Program

MT: Magnetic Testing

OHSAS: Occupational Health and Safety Assessment Series

OSHA: Occupational Safety and Health Administration

OI: Open Innovation

PD: Proportional Derivative

PIC: Programmable Intelligent Computer

PID: Proportional Integral Derivative

PIG: Pipeline Inspection Gauge

PRAC: Petroleum Research Atlantic Canada

PTAC: Petroleum Technology Alliance Canada

R&D: Research and Development

RF: Radio Frequency

RTG: radio isotopic thermoelectric generator

SAGD: Steam Assisted Gravity Drainage

SEMS: Safety and Environmental Management Systems

UT: Ultrasonic Transducer

UTF: Underground Test Facility

1. Introduction

For the business process in the petroleum industry it is crucial that there is high uptime of petroleum plants, good Health, Safety and Environment (HSE) conditions and simple logistics (Transeth et al., 2013). This goal has to be reached for offshore as well as for onshore sites of production and also for the transportation of the commodities.

The issues stated above need more and more attention along the industry, because the facilitation process of oil and gas, in the petroleum industry is gaining complexity. This fact shows the requirement of applications of new technological innovation in the industry for automation, remote supervision and control in different stages of production, transportation and environmental settings. This is the stage where the rising need, to implement robotics in the production and maintenance process, comes in place. (Wethe, 2012)

However, due to guidelines, standards and business requirements as well as poor distribution of non NOC's in the market does not allow durable utilization of robotics. Therefore, application of Open Innovation to the industry is crucial. Nevertheless, Open Innovation efficiency increasing is a long process and should start with same-level "playing field" creation, with the help of unification of variables, constraints, same level of evaluation and assessment as well as new improvements.

1.1 Context

Robotics has the potential to contribute significant benefits for offshore and onshore petroleum industry for the next decades, but in fact has nowadays often the problem of missing wide commercial availability (Transeth et al., 2013), which means that robotics is in some cases more expensive for the industry that it should be or the development period is complex. In the end, there is a big potential for the petroleum industry to increase profits, safety or production capacity when implementing more robotic technique in their production process. Nevertheless, this potential is barely used due to given economic, organizational and social barriers.

Therefore, this thesis shows state of the art robotics in the oil industry, especially in the case of robotic vehicles which move inside a pipeline for inspection reasons, so called in-pipe inspection robots. Moreover, the first time in this field all calculated influencing technological variables are covered and classified, which leads to a basic assessment and a 5-point evaluation method set for different applications due to different robotic devices locomotion in in-pipe inspection for hydrocarbon industry. In Chapter 4 there is an application of the 5-point evaluation method to five chosen different existing projects. Moreover, a new concept of robotic design which could perform better due to given requirements of the method is introduced.

Besides the technical part, different methods of innovation are covered in Chapter 1 to underline the importance of ongoing and efficient innovation processes for the use case and further development of robotics in the petroleum industry. Since the Open Innovation is becoming actual topic for innovation and robotic developments move from Outsourcing to Open Source and towards Open Innovation processes, variable assessment and project evaluations are essential to create the base for application of Open Innovation in in-pipe inspection robotics.

1.1.1 Petroleum industry and robotic deployment in the industry

The Global primary energy consumption is expected to rise (see Fig. 1: World primary energy demand till 2035 (Stavinoha et al., 2014)) but increased by just 1.0 percent in 2015, which is similar to the average growth rate of 2014 which lies by 1.1 percent, but is much under the ten-year average of 1.9 percent. This numbers reflect the lowest global growth rate since 1998 and underpins the need of new innovative production processes to increase profits and lower costs of production and maintenance when a decrease in overall energy demand occurs.

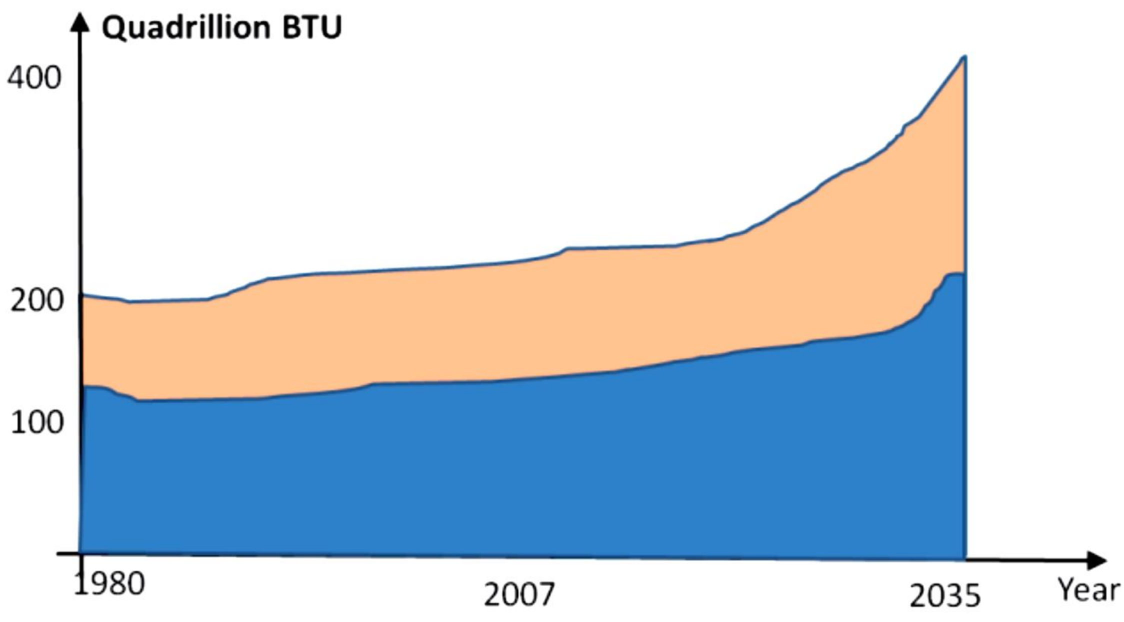

Figure 1: World primary energy demand till 2035 (Stavinoha et al., 2014)

Divided by the different fuel types, only oil and nuclear power can show growth rates, especially oil is regaining market share for the first time since 1999. Also the renewable energy sector is growing through heavy worldwide investments to an overall level of 3 percent of global energy consumption.

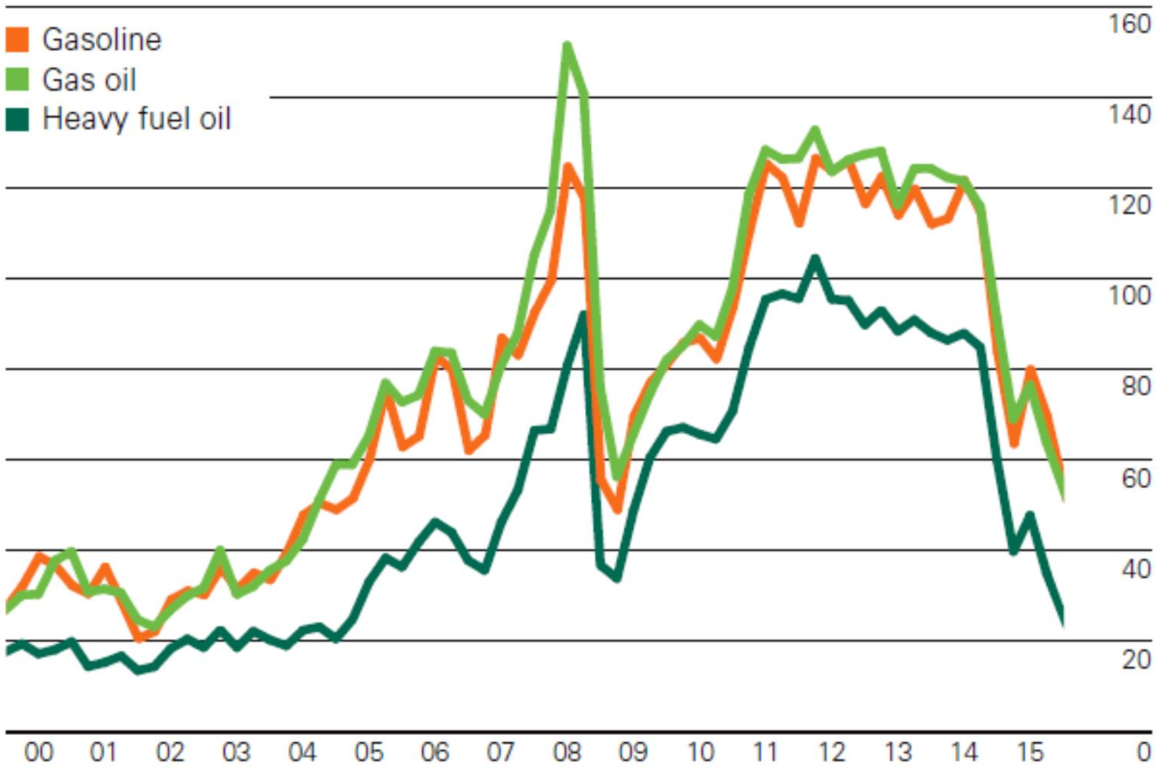

Figure 2: Price decreases in petroleum industry (BP, 2016)

The price structure of fossil fuels applies pressure the petroleum industry. For example, the crude oil price observes nowadays the greatest decline, around 47 percent for Brent, ever seen (in percentage terms it is the largest decline since 1986). Prices for natural gas are also declining, especially in North America. At the end of the day, oil remains the world´s leading fuel accounting for round 33 percent of global energy consumption. (BP, 2016) However, robotic deployment in this field is not yet in demanded level. Those decreases are shown in Fig. 2 virtually, covering 2000's.

However, from 90's on the usage of other type of fuels than oil related commodities also increased. As seen in Fig. 3 consumption of all type of energy sources increased till 2009. There was a slight decrease in 2009; however did not affect the consumption trend of the industry that much. Till today, all type of energy sources consumption follows increasing trend, nevertheless petroleum and its products have the biggest portion of the world energy consumption.

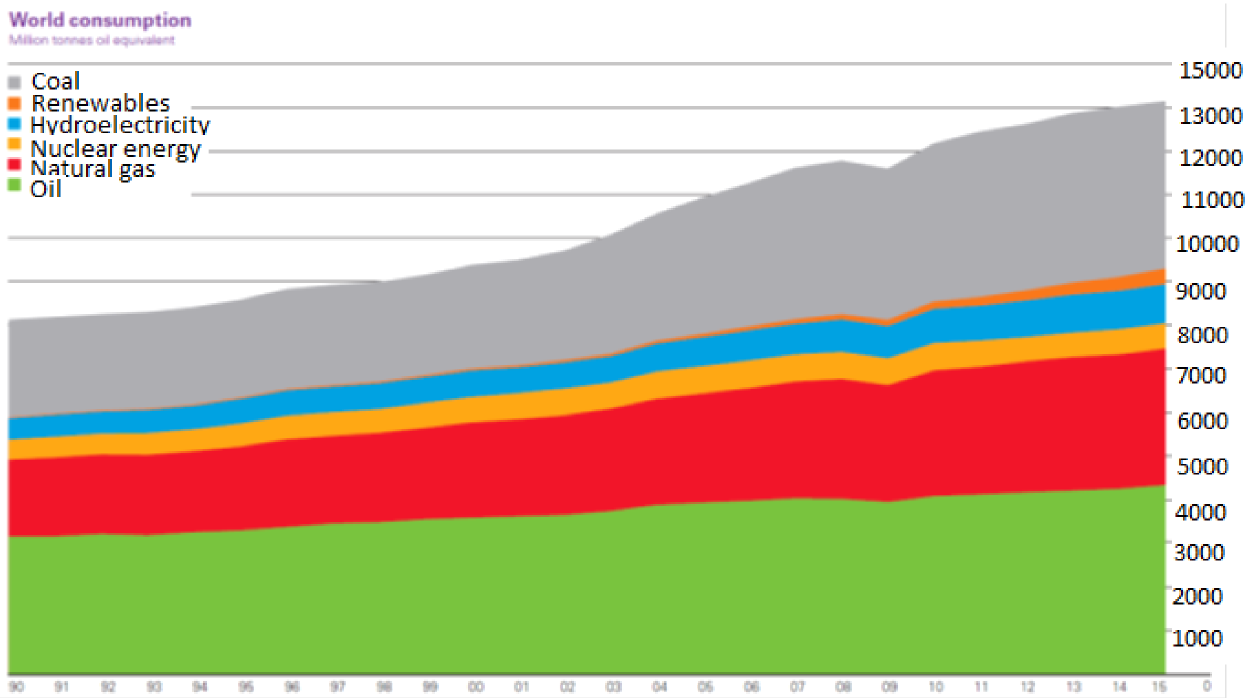

Figure 3: World energy consumption divided by source (BP, 2016)

A seen petroleum industry has never lost the importance among other commodities; however the processes are becoming more dangerous and difficult, where robotic deployment need arises. There are different use cases of robotic deployment in petroleum industry to show how they could contribute to the business of major oil companies. (Transeth et al., 2013) discussed the four general robotic classifications regarding to the use and business cases in petroleum industry.

- **Dangerous**: Robotic devices can help human personal on oil sites to avoid dangerous situations and maintenance tasks in the rough environmental setting at offshore as well as onshore operations. Operation areas are for example operation tasks on or below an offshore deck, operation on flame towers or maintenance tasks of oil or gas pipelines. Also helping out in emergency situation is another use case of robots in the oil industry.

- **Distant**: At offshore platforms the onboard manning degree differs from site to site. There are platforms which get visited only once a day, because a stay overnight is not recommended. The range fluctuates through the production sites from a monthly, a daily till to a constant 24/7 manning including overnight stays. For sites with low staff assignment it is important to ensure remote operation is possible regarding to an efficient production process. Robots can fulfill this monitoring gap and guarantee remote inspection and maintenance when no human is present.

- **Dull**: Robotic inspection and maintenance vehicles can execute monotone workflows on production sites, because they offer a higher repeatability rate and more frequent inspections than humans do, which can lead to an increase of failure prevention and less shutdowns of the production process.

- **Dirty**: This classification regards to the dirty and rough environment which can occur on production site and subsumes all kind of cleaning tasks.

Moreover, there are other possible cases of robotic use in petroleum industry which will be covered in the next sections as inspection tasks in which human work is either impossible, unnecessary, dangerous or inefficient.

1.1.2 Robot-based technology development in petroleum industry

Oil industry is a growing and wide industry in terms of new technological applications. Therefore, to minimize human force and for the efficient, sustainable and more accurate operations, petroleum industry needs some improvements and new technological benefits. There are plenty of research centers and institutes improving knowledge and new technologies for petroleum exploration and production.

The petroleum industry is focused on cost saving and cheaper exploration and production methods. Therefore, it is important to have the opportunity of being able to use new technological applications especially in discovery and recovery. Industry has a trend towards having one–time big investment in order to hold longer term costs less. This means that investment on a new application, that can be useful for long term discoveries and production, is efficient in terms of long term production. That also is the main reason behind the usage of pipelines as a main transportation tool instead of sea or road and rail transport. In short term, implementation of such big tools could be expensive but it saves labor costs and other relevant operational expenses of usage in long term.

There are many developments and researches for robot applications in petroleum industry, because of mentioned reasons above. They can be useful in each phase of discovery, extraction, recovery, production and transportation. The robotic deployment in petroleum industry background is covered in the previous subchapter. However, it can be mainly divided into exploration, observation, drilling, and production and control robots. One of the main objectives of such robots in petroleum industry is to supply and process the data in order to give information to the users.

"The 2010 BP disaster" in the Gulf of Mexico helped shift attitudes. Eleven men were killed when the Deepwater Horizon rig caught fire and sank. Statoil has projected that automation may cut in half the number of workers needed on an offshore rig and help complete jobs 25 percent faster former." (Wethe, 2012)

"Robotic Drilling Systems" consist of a series of robots to take over the repeatable tasks now done by deckhands, roughnecks and pipe handlers on a rig. Its blue, 10-foot-tall robot deckhand has a jointed arm that can extend about 10 feet, with 15 or so interchangeable hands of assorted sizes. The robot is anchored in place to give it better leverage as it lifts drill bits that weigh more than a ton and maneuvers them into place. The company is also collaborating with researchers at Stanford University on a three-fingered robot hand embedded with sensors that give it a touch delicate enough to pick up an egg without crushing it. (Wethe, 2012)

Oil production robots are also used in places which are hard for a human to get in, such as underground holes and inside pipelines. Leading companies in energy sector are heavily investing in new technologies such as BP, Statoil, Chevron and etc. For example, Norwegian Oil Service Company is developing a robot for drilling and the management claims it would reduce the drilling time by 50 %. (Faucon, 2013)

In an Australian company, a research and development is going on in order to improve the application of robot technology in underground oil field evaluation. This robot is called "CSIRO's autonomous and wireless down-hole robot". Main task of this robot is measurements and sending the data of variables in production wells, such as pressure, temperature and flow rates variables. This robot is on development phase and hasn't been used for industrial purposes yet.

There are also robot applications in logistic part of oil industry. For example, SLOFEC inspection robot is used for checking and maintenance of pipelines. It is developed and used by an oil and gas company in USA in order to take care of their pipeline network which is over 10.000 km. This robot can easily transport within the pipelines, between the valves, and measure some variables in order to supply information of pressure, oxygen and nitrogen rates, temperature and flow rate in the pipeline. It can shut itself down in case of emergency or unexpected oxygen rate in pipeline to avoid explosion.

Statoil, Norwegian Oil Company leads the market in terms of technological innovations in laboratory facilities of oil production. The company heavily invested in laboratory technologies in order to have ability of better products and deeper production. They are creating robots mostly for the maintenance of equipment and control over. Statoil has its own creation of lab for offshore facilities, which consists of several robots with huge range of abilities. These robots can operate the manual valves and can measure pressure, sound, vibrations, temperature and gas. All the sensors and operating system is applied by KUKA. This laboratory robot has a collision avoidance system implemented because of avoiding crashes of robot with processing parts. Since this robot is planning to be 7.5 tons, crashes are important safety problem to deal with.

The Liquid Robotics Oil Gas, a joint venture with Schlumberger created a semi-autonomous system for pre-exploration, production and abandonment phases of offshore oil recovery. This allows the company to produce reliable information before constructing platform, then any climate and other condition changes during recovery, and environmental friendly abandonment. It is planned to implement in Australian offshore areas for oil and gas recovery.

1.1.3 HSE and standards in in-pipe robotics

Petroleum industry is one of the biggest industries that heavily covered by safety requirements, legal boundaries and international and organizational standards. There are several standards and legal requirements in petroleum industry. Due to the scope of this dissertation only pipeline inspection requirements as well as robotic deployment standards will be discussed.

One of the main tasks of robotic devices along the whole value chain of the petroleum industry is to improve HSE (Health, Safety and Environment) and efficiency at production sites where dangerous, distant, dull or dirty environmental settings can occur. This task of robotic deployment in the industry can be seen in many of the organizational standards. (OSHA, 1987) (ISO, 1995) (ISO, 2011b) (ISO, 2011a)

The motivational background of inspection is to foresee the upcoming cracks, leakages and other deformations in the pipeline in order to be able to minimize risks and hazards, so inspection is not only a task for economic reasons it is also a requirement of efficiency, environmental risks, risk management and functionality in terms of quality management. Since inspections are closely related to risk management and environmental procedures it is strictly regulated by local regulations and standardized by norms and standards. Therefore, inspection is also involved in OHSAS, ISO and other standards institutions and organizations guidelines of risk assessment, risk management and whole health and safety management systems.

From another perspective it can be concluded that inspection is a task to ensure functionality of pipelines and if GPS (Geometrical Product Specifications) fulfills the functionality specifications of pipelines. From this perspective inspection can be seen as a tool of quality management systems as well as health and safety management systems since it intends to minimize the risks and number of occupational accidents. The OHSAS 18001 conduces as a guideline which is capable of being certified such management systems and consists in ISO 9001 for quality management systems and ISO 14001 for environmental management systems. Furthermore, ISO 31000 can be also considered due to risk management and risk assessment standard guidelines. (ISO, 2009) (ISO, 2004) (ISO, 2015) (OHSAS, 2007)

There are a few requirements for pipeline holders regarding the pipeline inspection, because they are forced to insure that the pipeline gets inspected in defined time schedules. When for example a system for pipeline integrity, like an inspection robot is in use, regarding to AS 2885 (Standards Australia, 2016), inspection tasks have to be fulfilled at least within 7 years after entering the operational phase and in addition after that period of time at least once in every 5 or 10 year period based on detail specifications in the standard.

The (ISO, 2011a) standard governs the petroleum and natural gas industry, specially the part of piping, because it defines the requisitions for design, construction as well as for inspection and testing of pipelines for the whole industry sector and its facilities like chemical, petroleum or natural gas plants or platforms. For example, the standard is applicable for offshore oil and gas platforms, chemical plants, tank farms or gas processing facilities as well to packaged equipment piping which interconnects different pieces of equipment within a packaged assembly to use it in the petroleum industry processing.

In addition to that, there is also a need in robotic use in petroleum industry to certificate operations in explosive atmospheres. There already a few robots which have passed these operation requirements and are therefore able to operate safely in this kind of environment, but there are robots where the power supply and the control part are not included in this approval (Transeth et al., 2013).

Some robotic devices are certified for so called ATEX zones. ATEX stands for to European Union directives which define the tools and equipment in explosion endangered areas. For example, Sensabot, an inspection robot which consists out of a mobile base and a two-joint arm has been developed to fulfill the requested requirements for ATEX Zone 1. At the moment there are no robots available which have been constructed for ATEX Zone 0; this shows the need for further developments in this sector which should improve robot´s durability in dangerous environments over a long period of time. (Transeth et al., 2013)

With help of standards, regulations and core values organizations create Safety and Environmental Management Systems (SEMS). The scope of SEMS is broad, as shown in the following quotation from one of the rules of such a system:

“. . .your SEMS program identifies, addresses and manages safety, environmental hazards, and impacts during design, construction, start-up, operation, inspection, and maintenance of all new and existing facilities, including mobile offshore drilling units (MODU) while under BOEMRE jurisdiction and Department of Interior (DOI) regulated pipelines SEMS

Testing, inspection, calibration and monitoring programs for critical equipment should be established. Programs may be required for environmental protection compliance monitoring. The management plan should document the technologies utilized and measurement systems used for compliance. Such programs should include the following items…” (Sutton, 2014)

Also the human effects of Health and Safety are crucial, because field managers or production foreman has to deal with this kind of threat to ensure an effective and successful management of robotic devices in hazardous environments. The overall performance has human, material, intangible, legal, personnel and also financial effects which should be on focus of every corporation which is part of the petroleum industry.

There is also the field of tele-operation which comes in place when an industry is forced to handle with HSE environments. In the guidelines for robotics and safety published by the Occupational Safety and Health Administration of the US government (OSHA, 1987) is stated that tele-operation is not only able to increase safety conditions, it is also able to increase production. Tele-operation gets used in various fields like offshore oil and gas exploration or in hazardous environment settings. The subcase of Tele-inspection is nowadays more and more in use for fulfilling robotic inspections by taking advantage of the measurements of various sensors to perform better in the given tasks in petroleum industry. The terminology used for hazard and risk is different among countries but in general it is defined as (OSHA, 1987):

- A hazard is something that can cause harm if it gets not controlled.
- A risk is a combination of the probability that a particular outcome will occur and the severity of the harm involved

Beside those definitions and standards, there are several inspection methods which are in use, applicable or non-applicable due to several reasons. All tools and methods is not covered in this work due to work delimitations, however detection technology table can be seen in Appendix C.

Standards in the industry are limiting the development; however, they are essential for a sustainable safety guidelines formation as well as for the right terminology in use. With the help of those regulations and standards the same level playing field created for the organizations in same industry and it helps them to have clear view for improvement. However, classical approach is being developed and modern methods are implemented, which is the topic of following subchapters.

1.2 Innovation Overview

Innovation is one of the key factors when talking about competitive advantages over other firms as well as in market growth. The classical approach for the last decades to do innovation in the petroleum industry was to ensure that you had a big research and development (R&D) department which insures the innovation progress of an oil and gas company as a whole.

1.2.1 Methods of innovation in petroleum industry

There are many researches that show the implementation of information and communication technologies forces firms to think new about their global strategies in terms of technological innovation. Out of this fact, researchers have tried to combine the global strategies of international firms with network formation (which means to collaborate with other stakeholders). (Chesbrough et al., 2006) combined this to his Open Innovation concept, which consists out of global strategy concepts as well as concepts out of the Open Source software development. (Pires and Urbina, 2009) Since the robotic development is being accelerated by wide use of Open Source platforms, the Open Innovation applications are essential for gaining more competitive advantage, to bring innovations further and for efficient innovation actions.

Another and little older projection to come from closed to a more “open” innovation setting is the Lead User Method which is a kind of user innovation approach and was developed from (Hippel, 1986). Here lead users (which can be individuals as well as organizations) get first identified and in a second step included into the innovation process, which helps firms to develop precise innovative solutions for their problems, especially in the industrial setting. “These “lead users” were individuals or organizations who had experienced needs for a given innovation earlier than the majority of the target market” (Hippel, 1986)

These concepts are now presented in the next two subchapters in more detail.

1.2.2 Open Innovation Paradigm

The concepts of Open Innovation ((Chesbrough et al., 2006); (Chesbrough et al., 2014); (Chesbrough, 2004); (Chesbrough and Appleyard, 2007) and (Chesbrough, 2003)) suggest firms who would like to be more innovative to use internal as well as external sources for their idea generation. Inside the company this can be fulfilled through cooperation’s among different departments or external through the attraction of other companies or universities. It is clear that this kind of radical approach has to be adapted to the firm’s strategy. For complex industries like the petroleum industry, it is more important to implement partnerships than in other industries, because of the different innovation setting in more complex production systems. Especially oil and gas industry is developing many different product types, from small maintenance sensors to oil pipelines or offshore platforms. There is a need for high complex and performance service and product solutions to fulfill their special requirements. This new innovation process should help the industry to increase efficiency and reduce risks and cost of operation. Especially university knowledge plays a major role in indicated sense. (Pires and Urbina, 2009) (Hakkim and Heidrick, 2008)

With this innovation setting there are also opportunities for new business models along the industry. (Chesbrough, 2006) (Chesbrough, 2011)

a. Toolkits of Open Innovation in petroleum industry

One approach to implement Open Innovation in the petroleum industry is to identify the important steps needed for distributed research and development projects. (Pires and Urbina, 2009) found three important stages, which are:

- **Project lifecycle**: layer of project development
  - Defining project requirements
  - Defining of necessary areas of knowledge for reaching the project goal
- **Competence management**: layer of knowledge and team allocation
- **Strategy of organization**: focus on the strategy of the organization

All cooperating partners should understand the same about the project and its goals for the sake of sustainable development.

The combination of these three steps leads to a working project coordination, especially when unforeseen circumstances occur. (Pires and Urbina, 2009) In this case there is much higher need for coordination in R&D projects. In the special use case of (Pires and Urbina, 2009) the projects lifecycle is a simulation software for pipelines in the oil and gas industry. For collaborative team work they used wikis and websites as well as file sharing applications. The whole project lifecycle is shown in Fig. 4, which shows as well a complex cooperation between different parties like the Brazilian university, the oil and gas industry of brazil, a company out of the petroleum industry of Norway as well as a Brazilian investments agency called FINEP (Pires and Urbina, 2009). The university is bringing knowledge and product development Know-how, the Norwegian company provides as well industry knowledge, main client of the researchers is the Brazilian oil and gas industry and FINEP gives the required financial resources.

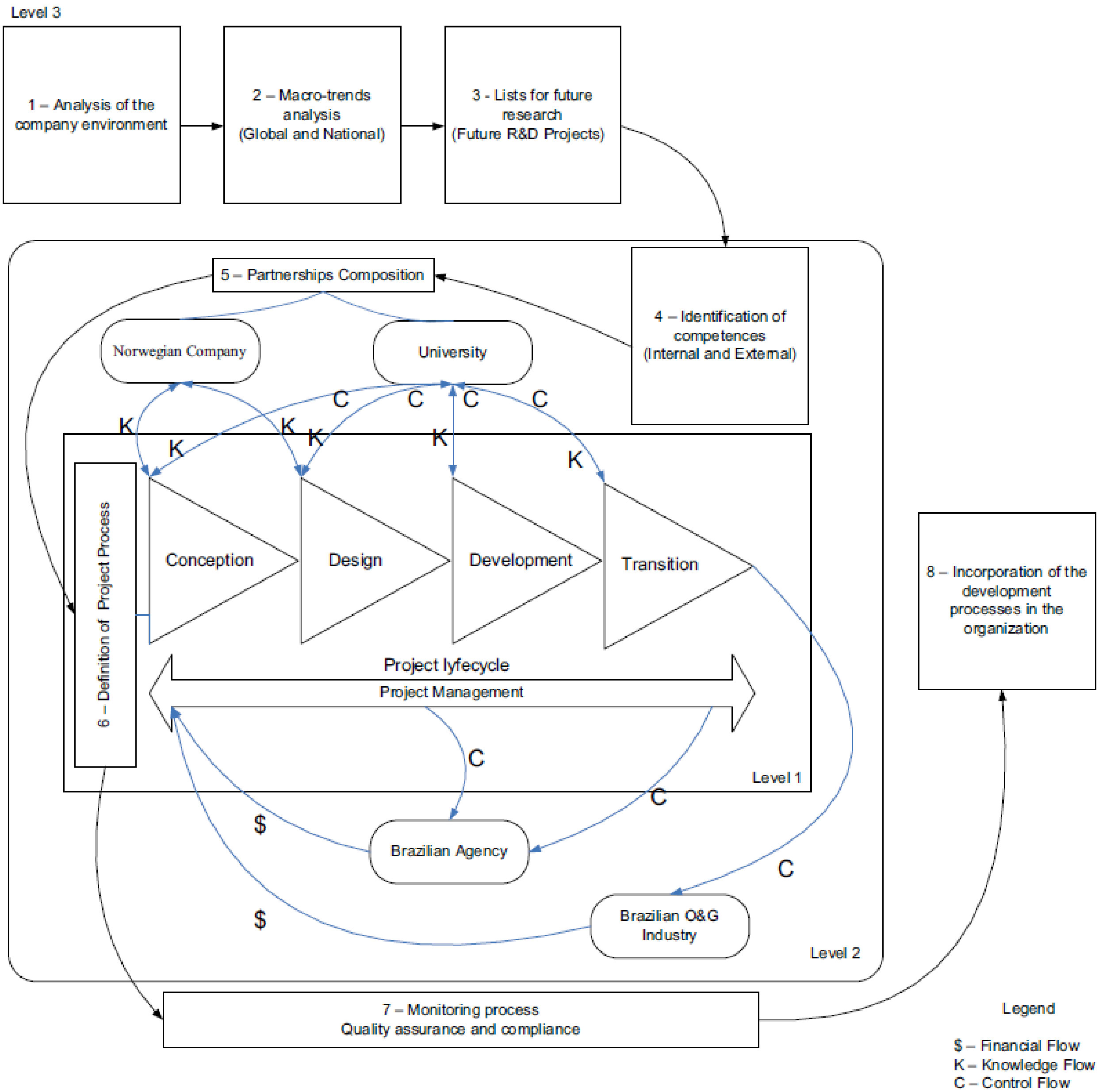

Figure 4: Model for coordination of R&D projects (Pires, Urbina 2009)

This practical example in Fig. 4 out of the oil and gas industry shows very well how the implementation of the Open Innovation paradigm can lead to an increase in innovation efficiency through the integration of different partners to work together on the best possible solution to a specific industrial problem. Another approach to implement Open Innovation in petroleum is the Open Innovation platforms from Shell called “Shell GameChanger” and “Shell TechWorks”. In the Shell GameChanger program unproven ideas from innovative people can be suggested online to solve problems in the energy sector (Shell, 2016a). In the “Shell TechWorks” program shell collaborates witch technological entrepreneurs and Start-ups outside the oil and gas industry to improve industry innovation (Shell, 2016b).

The Shell approach had one of the biggest impacts and starting point for deploying Open Innovation in petroleum industry. It was a necessary and maybe a late decision; however Shell was innovative enough to embrace the change, caught the trend and had the clear concept on open innovation processes in Petroleum industry. The process from the suggested idea to solution for the petroleum industry is shown in Fig. 5.

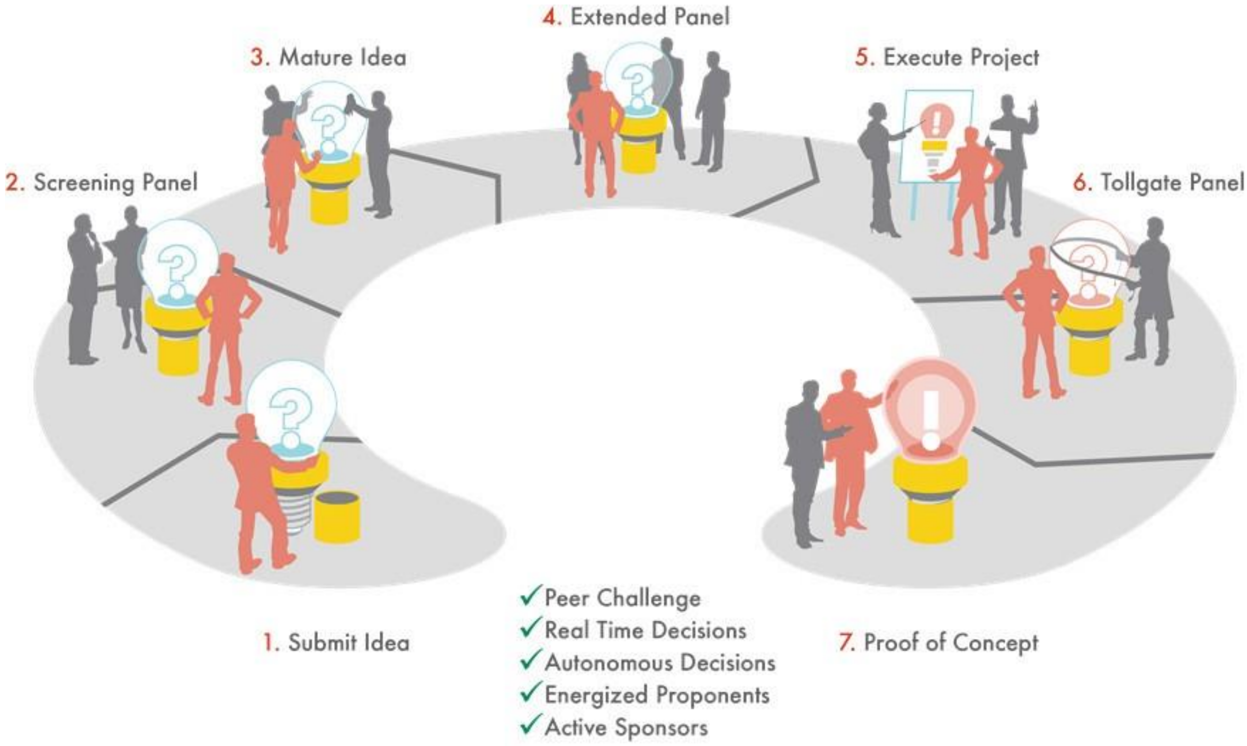

Figure 5: 7 Phases of the Shell GameChanger program after idea submission (Shell, 2016a)

1.2.3 The Lead User Method

As described in Chapter 1.2.1, the lead user concept is searching for lead users which can enhance to innovation process. (Olson and Bakke, 2001) In the first step an interdisciplinary team gets built and the target market of the product or service has to be defined as well as the level of involvement in the innovation process of the participating lead users. In the second step needs and trends along the industry should be identified. To reach this goal there are often interviews with industry and technology experts. This should lead the firm in the end to the selection of attractive trends which are aligning with their business model. In step three the lead users get identified and they are screening together first ideas and solutions. In the last phase of the lead user method the company works together with the lead users on a connectional design which gets in the end evaluated as well as documented as seen in Fig.6.

Also the lead user method can help firms in the petroleum industry to improve their product and service development and to reach a competitive advantage among their competitors.

In Fig. 6 the main steps of the lead user method are presented. As mentioned those steps are starting the lead user process, identifying needs and trends, identifying the lead users and designing the concept from the outcomes of first three steps.

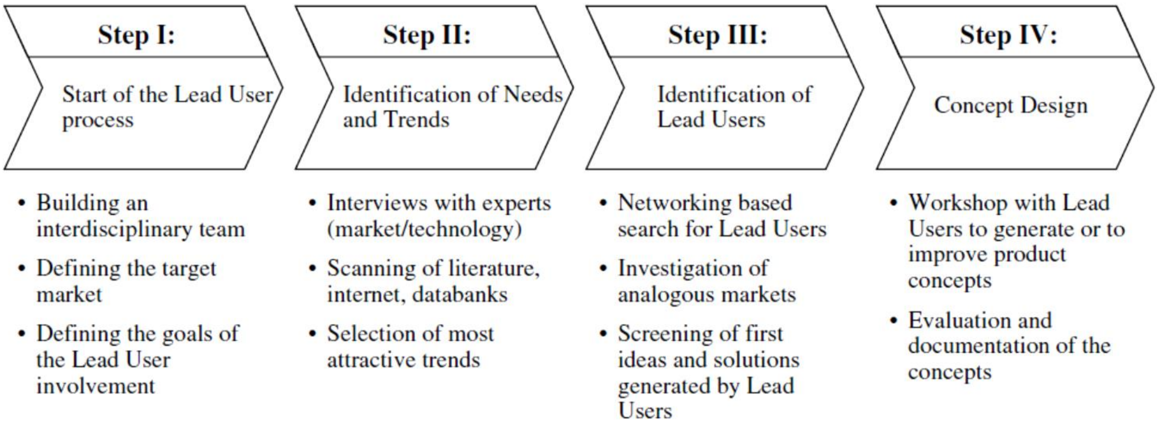

Figure 6: 4 main steps of the lead user method (Luthje and Herstatt, 2004)

1.2.4 Obstacles, barriers and challenges of innovation

There are general obstacles, barriers or at least challenges that can slow down or hinder innovative processes in the petroleum industry. For a robust development in innovation such barriers should be well studied. The barriers can be divided into different groups, namely strategic barriers, organizational barriers and cultural introspective barriers.

a. Strategic barriers

The following specific strategic barriers can be identified for the petroleum industry (Robert Peterson et al., 2014)

- Near-term focus
- Lack of clarity of research and development objectives
- Imbalances in resource allocation

For example, imbalances in the allocation of resources can occur when an organization has to handle technical long-term challenges. This can lead to a rising gap between the general business strategy and the technological strategy of an oil and gas company, which can result in ambiguous research and development objectives and as a consequence in unclear resource allocation.

b. Organizational barriers

(Robert Peterson et al., 2014) and (Burcharth and Søndergaard, 2011) as well identified organizational barriers which can slow or weaken innovation processes in the oil and gas industry. For example, when there are kind of functional silos inside a company, which are handling research and development or operational tasks, this organizational structure can lead to an ineffective cross-functional approach, compared to a collaborative one. Organizational barriers are:

- Functional silos
- Reactive R&D organization
- Lack of cross-business collaboration
- Unwillingness of employees to transfer knowledge

c. Cultural and introspective barriers

The cultural and introspective barriers can be divided like the following and is probably the most important challenge when talking about innovation (Robert Peterson et al., 2014) :

- Conservative
- Low risk-tolerance
- Unwillingness to experiment

A slowdown in the innovation process of a petroleum firm can occur, when the organization is too passive or conservative in terms of innovation, because a leadership role can strengthen firm’s position in finding new solutions to the problems that should be solved in the industry.

1.3 Problem definition

The problem is defined in several aspects. First of all, the lack of innovation methodology, obstacles for innovation and need for Open Innovation guidelines is an essential issue for the petroleum industry's robotics. Petroleum industry is one of the commodity industries that need much specifications and standardization or framework definition to embrace the innovation and to apply. There is a need of the frameworks of innovation in the industry. On the other hand, there has not been any variable classification and standardized variable list for robotic innovation to achieve the mentioned frameworks till now. Moreover, due to the absence of whole variable definition and classification, a reliable and robust evaluation method is missing in this area. Therefore, the assessment is not being done properly for users, developers or firms to assess the existing projects and to evaluate the market in terms of specified needs.

On the other hand, a common evaluation method is missing in this industry to assess the robotic development or to specify requirements for new innovations.

The problem is discussed in details in following subchapters such as the comparison of the innovation processes and improvement actions and main research purpose which is to create an assessment method out of variables of the industry and evaluate the case projects to obtain evaluation for users, developers and the firms as starting to draft guidelines for Open Innovation efficiency. The whole variables set classification and definitions as well as the assessment criterions formation are new in this field. Also, such a research has not been done for an efficient assessment of existing projects and an effective step for framework formation of Open Innovation in pipeline robotics previously. On the other hand, there is an essential need of new approaches and innovative concepts of robotic developments in this field.

1.3.1 Comparison of innovation approaches

The next subchapters discuss the most common innovation approaches and compare them to the Open Innovation paradigm.

a. Outsourcing versus Open Innovation

In the last 20 years' different circumstances have weakened the leading position of major oil companies worldwide. The oil and gas reservoirs are under the control of National Oil

Corporations which handle the production as well as the exploration part. Furthermore, the main research and development action of these companies lies in the hands of service companies like Schlumberger or Halliburton, because the major oil firms have outsourced their innovation for them. This means that these firms have lost the control over technology, and in addition the service companies are investing a lot of money in their research and development departments to gain more and more intellectual property. Many people in the literature suggest that it is time for a change, in fact time to reorder the relationship between the oil firms and the service companies as well as with other players in the market (e.g.: National Oil Companies, other Majors). They must have the new goal to regain their leadership about the research and development actions, which on the other hand means to invest more in this sector. (Pellegrini et al., 2012) (Pfeffermann et al., 2013)

Some companies (e.g. Eni) have recognized that they have to collaborate more with other stakeholders to move from outsourcing to a more Open Innovation approach. In the paper (Pellegrini et al., 2012) they described the main differences between this two approaches, which is shown in Fig. 7.

		PERSPECTIVES		
		Direction	Type of partner	Organisational form
Outsourcing		Outside-in	Provider(s)	Contracts/agreements
OI		Outside in, Inside-out, Coupled process	All the knowledge sources (customers, competitors, Universities, …)	Corporate Venture Capital, Non-equity alliances, Equity alliances, Acquisitions
Implications of OI on	Competencies	Complementary character of internal and external innovation-related activities	- Exposure to knowledge from different sources - Exploitation of complementarities with partners	
	Costs	Inbound - Acquisition expenses - Costs connected with the exploration/selection of external innovation sources Outbound; costs due to the necessity of - building a strategy to choose the internal resources to be revealed - putting into practice the licensing of technologies	Costs of coordination Strong managerial attention	OI proposes alternatives with different reversibility/commitment implications and hence costs; outsourcing is based on contracts/agreements characterized by high reversibility and low commitment

Figure 7: Differences between outsourcing and Open Innovation (Pellegrini et al., 2012)

b. Open-Source robotics versus Open Innovation in robotics

Open Source and Open Innovation are concepts that share many similarities. Often when firms, especially in the software industry, use the Open Source concept, they are able to utilize the Open Innovation paradigm as well, because both definitions fit in many points. In both approaches companies use a wide pool of external innovation sources and looking for alternatives for doing only internal research and development actions. For many years, also in the robotics industry, developers use third party suppliers of complementary software products (ISVs – independent software vendors) for their own developments instead of going ahead and use the traditional concept of vertical integration. In fact, Open Source can only be Open Innovation, when it has an underlying business model. On the other hand, there are many Open Source projects out there they only get developed by a strong ideology or a non-monetary use (e.g. GNU-Project). (Pires and Urbina, 2009) (Chesbrough, 2006)

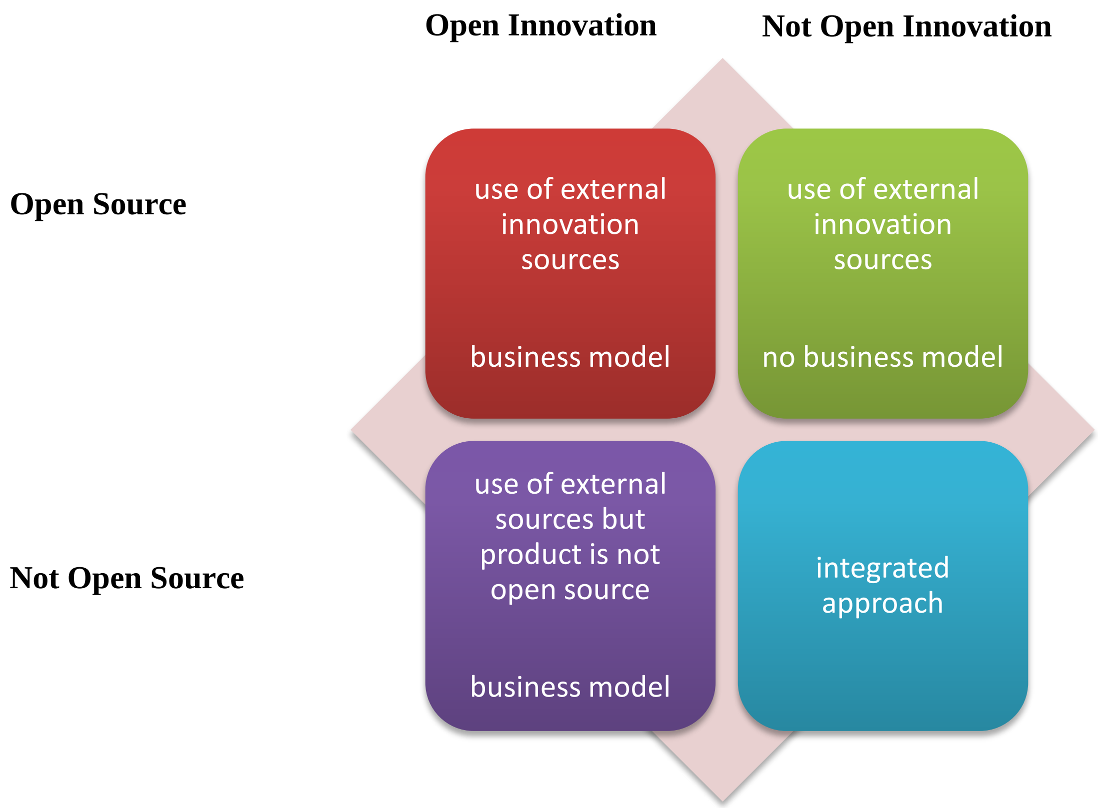

Figure 8: Intersection of Open Innovation and Open Source

A second case is occurring when there is Open Innovation but not Open Source. When on the one hand a product lowers the market barriers for other competitors to enter the market but on the other hand the firm is not able to use the underlying business model to gain profit out of their innovation and has to leave the market. This example has taken place in the software industry in 2004, when IBM was forced to leave the personal computer market, because they can´t get enough revenue out of their Windows computers using Intel components. When there is no usage of Open Source as well as Open Innovation, company’s use a traditional integrated approach, where there is no need for third party ISVs. (Chesbrough et al., 2006)

Fig. 8 represents the main similarities as well as the differences of Open Innovation and Open Source approaches in the industry. As seen, using external innovation sources in the business model is the common approach in both types of the innovations. However, using external innovation sources but not applying it as the business model is not common for Open Innovation, but it can be considered in Open Source approach.

1.3.2 Innovation efficiency improvement actions in industrial robotics as well as in petroleum industry

The Open Innovation paradigm has not only the goal to boost new product development; it has the task to boost internal as well as external innovation capacities. With valuable external knowledge a firm is able to increase their own strengths and the speed innovations can accrue as well as use idle internal knowledge align with external resources to enter the market. However, in many industries as in the petroleum industry they are selling commodities, in this case especially oil and gas. In this industries new product development is very difficult and therefore often no alternative. In this case a petroleum firm should primarily find a strategic driver which allows them to gain a competitive advantage. In addition, the company should look on other players in the market to find technological innovations from other firms, which can speed up and improve the finding of a key driver to gain competitive advantage. That this goal is possible, the petroleum firm has to set up a network or an innovation ecosystem which includes these technological innovation companies. This means that innovation made in the technology sector by one firm can lead to competitive advantage for another one. Therefore, there should be no direct link from Open Innovation to new product development; we should not forget the specific drivers that can help firms to gain a competitive advantage. (Pfeffermann et al., 2013) (Chesbrough et al., 2014) (Pires and Urbina, 2009)

For example, in the crude oil business many large oil companies are operating. These firms sell their commodity and not new products to the market. For the oil industry a company can find various strategic drivers that can improve the competitive advantage against competitors, for instance quick finding of large oil wells as well as effective drilling of these sources and efficient allocation. Therefore, the oil industry is dominated by big firms with large research and development departments, to increase the own competitiveness which depends on diverse technologies that exalt the effectiveness of the exploration and extraction process. The firms have to execute the new wells before their direct competitors can do it. The big oil players have to confidence in oil service companies as for example Schlumberger, that they are developing new exploration and extraction methods and tools. The oil service industry is the part of the industry, where the innovation is a daily need to keep alive, and therefore outstanding in the energy sector. This is also reflected by the intellectual property firms like Schlumberger owns. Firms working in the oil service industry hold in general more patents than big integrated oil firms. This means that when an oil firm decides to work together with such a company it can gain a competitive advantage out of the leading-edge technology developed there. For example, they can start a strategic partnership or a research program and finance it alone or together to develop drilling and exploration technologies further on. Of course there are exclusive use contracts, which insure that the oil company can gain the technological competitive advantage for a couple of years. The use of the Open Innovation paradigm allows oil companies to improve their innovative efficiency further on and tightening their market position against competitors. (Pfeffermann et al., 2013) (Chesbrough et al., 2014)

For example, in Canada there are different energy agencies which apply the methods of Open Innovation. One is the Alberta Energy Research Institute (AERI), a nonprofit organization which promotes collaborative research to increase the effectiveness (in a financial, environmental and safety performance way) of the Canadian upstream conventional oil and gas industry to boost innovation in this sector. The AERI makes energy research as well as technology tests and transfer, in oil, gas, heavy oil and oil sands. The institute absorbs knowledge and investment capacity from firms belong the industry, the local government and universities. (Hakkim and Heidrick, 2008)

Also the Petroleum Technology Alliance Canada (PTAC) is an organization which provides research and development to strengthen the safety, financial and environmental effort of the Canadian upstream oil and gas industry, in a nonprofit way. The honorary members are incorporating producers, suppliers as well as researchers and the government. The goal of the institution is to improve the collaboration in research and development between these stakeholders. The institution acts like a knowledge broker, because it brings those who have prospective research and development solutions together with the people who have innovative problems or opportunities. (Hakkim and Heidrick, 2008)

Another public private partnership formed by the Canadian government is the Petroleum Research Atlantic Canada, shortly PRAC. It promotes research and development made in the petroleum industry and collaborates with universities, firms out of the industry and the government. Main goal of the company is awareness creation to increase the attention of petroleum related R&D actions in the economy. PRAC has also good contract and resource connects to stakeholders in the Atlantic Canada region. (Hakkim and Heidrick, 2008)

This example underpins how important technological innovation is for the whole energy sector. This transfer of knowledge leads to an increase in the research and development efforts. The starting point for Open Innovation was the computer industry few years ago, now more and more firms out of the energy sector apply the concept of Open Innovation. Open Innovation brings a continuous flow from knowledge and technology among the research and development teams in different firms and enables a new network that moves the whole industry further on. (Hakkim and Heidrick, 2008)

A case study conducted by (Hakkim and Heidrick, 2008) on the Albertra Oil Sands Technology (AOST), which was described above and the Research Authority (AOSTRA) Underground Test Facility (UTF), was able to show the positive influence of Open Innovation in the research and development process in the showcase of the petroleum industry. There are also suggestions how to develop and manage such projects with an innovative consortium. In the past oil companies relied on their own research and development departments and well trained workforce, cause of competitive reasons. In the 1970s many of them perceived that other companies have the same issues regarding to research and development. Therefore, also government participation in the R&D process was gladly seen, for example with funding the process as a whole or with granted tax credits. Regarding to these developments it comes to the foundation of a research consortium for the project to evolve a new steam assisted gravity drainage technology for in-situ recovery of bitumen. Diverse companies of the oil sector (for example, Shell or Chevron) as well as the Canadian government take part in this formed consortium. After this collaborative development process, the stakeholders gained many benefits out of this cooperation for example, a worldwide intellectual property free usage of the technology, over 8 % of the leasing gains or free training of the own workforce on this leading-edge technology. For the industrial and commercial usage of the steam assisted gravity drainage technology for in-situ recovery of bitumen (SAGD), firms have to gain a license (at a convenient market price) from the local government. The main focus of the leasing model is now to enable a knowledge transfer between the involved parties and a practical application of the developed technology. Through this development, the production costs for synthetic crude oil in this area could be lowered significantly. Out of this project in Canada, the China National Petroleum Corporation and the JAPEX Oil Sands Ltd, which were both participants of the consortium, applied the technology in foreign countries. This shows that the output of the Open Innovation approach in the petroleum industry can help firms to reveal and reach economic success as well as improve the innovative effectiveness. (Hakkim and Heidrick, 2008)

1.3.3 Research purpose

The purpose of this dissertation consists of several aspects; firstly, the study intends to explore the feasibility and justification of Open Innovation that brings efficiency in petroleum robotics innovation processes. This was the topic explained till this part of the dissertation.

Secondly, a review of existing projects will be conducted within the industry which will be the topic of Chapter 2. Furthermore, the study intends to define and classify all relevant parameters and constraints of in-pipe locomotion first time in this field in order to achieve standardization in the variable assessment within locomotion planning for in-pipe inspection robots. Mentioned definitions and classifications are covered in Chapter 3.

Then, out of classified variables, evaluation method criteria should be defined which arise from the evaluated parameters. Finally, those criteria should form an assessment method which will be called 5-points evaluation method and will be applied to several chosen applications to obtain evaluation results of different development projects in Chapter 4. In the same chapter new robot concept which is expected to perform better among the competitors will be suggested and evaluated in the same way. Finally, the results will be compared due to changing weight factor from user's point of view, the developer's point of view as well as the firm's point of view and relevant suggestions will take place as well as a novel design concept for an in-pipe inspection robot will be presented, which is covered in Chapter 5.

a. Research background

In order to achieve the dissertation purposes research background, motivations and acceptances should be covered. First of all, the research covered mostly found scientific papers and research materials of the in-pipe inspection robots and results are within the information gained from found materials. Also discussions with technology developers and interviews supplied an overview and information to maintain the structure and to achieve research goals.

As indicated in Fig. 9, the guideline formation is a long-term process and needs to have collaborative work. However, a bottom-up approach in this field requires defining and classifying the variables of one topic – in this case the in-pipe inspection robotic locomotion- and start from this point. Then as shown, the variables should be classified and evaluated. Out of the results assessment criterions should be arises and forms an assessment method to evaluate existing projects as well as to evaluate upcoming developments. Then the results should be discussed and gaps should be found to develop the method and in general to improve the guidelines for an efficient Open Innovation action.

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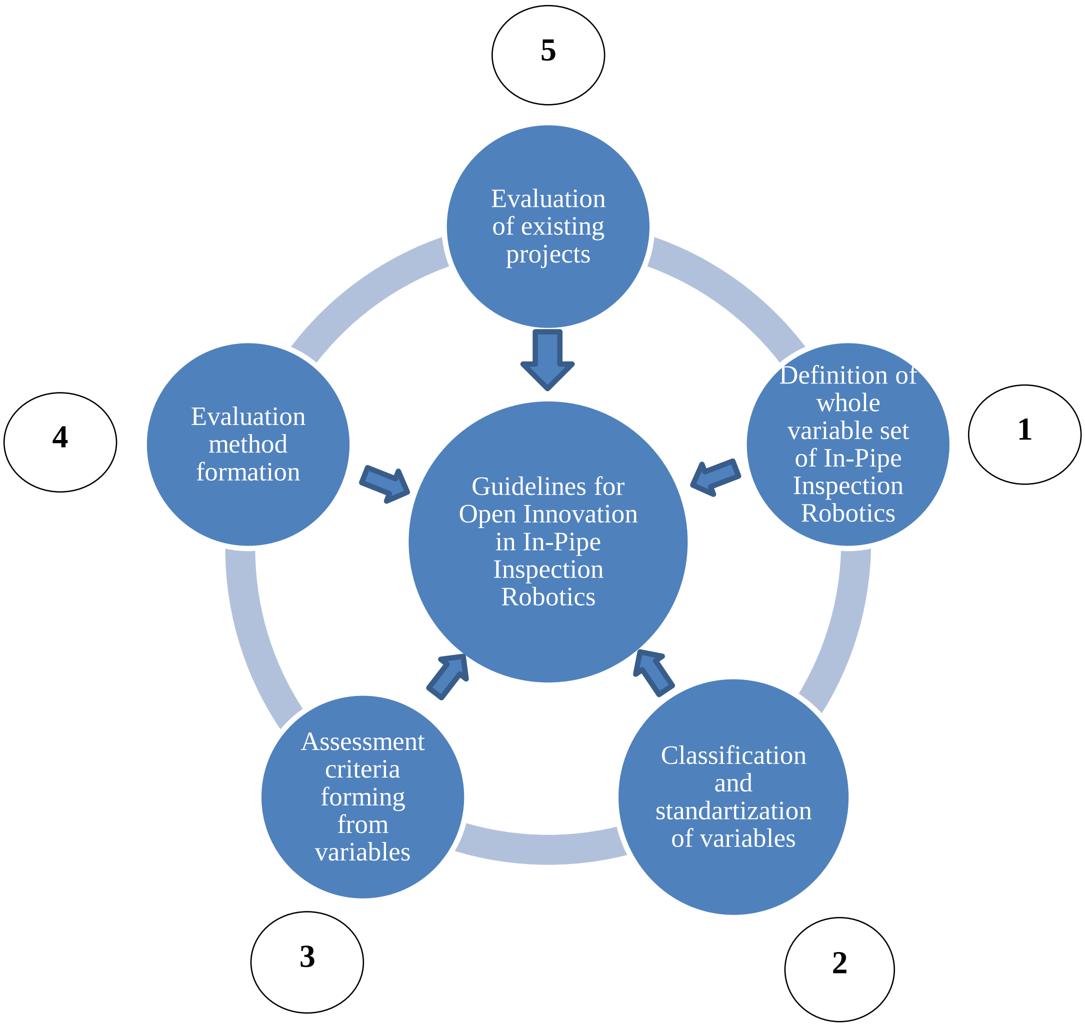


Figure 9: Initial steps of forming guidelines in Open Innovation in petroleum inspection robots

b. Research questions

In order to fulfill the research requirements and fit the research purposes there are several points to be covered. In order to achieve those goals, considering the research background following research questions arise:

- What are the traditional evaluation methods and the limitations to be use in a reliable market analysis?
- What are the variables of locomotion of in-pipe inspection robots that creates and evaluation of constraints and form assessment criterions for the purpose?
- What assessment criteria should be considered to form an efficient evaluation of the development projects and how the variables form the criteria?
- How are the development situations for the robots in this field and the comparison results of existing projects?
- What are the gaps in existing projects and what to offer for improvement of Open Innovation efficiency in order to create the reliable, robust and efficient in-pipe inspection robot?
- And mainly, is there a solution which would cover most of the requirements in the industry?

In order to answer the research questions, a qualitative analysis of the variables and criteria as well as the quantitative analysis of the robot projects should be carried out.

c. Research delimitations

As shown above in Fig. 9 guideline definition and formation for Open-Innovation in robotics is a complex and long-term research area for more than one dissertation's borderlines. Although a complete offer is necessary, the borderlines of this dissertation allows to cover first circle – 5 steps of the research and is not enough to cover the whole process. Therefore, the processes after evaluation results and comparison are out of the scope of this dissertation.

Due to the space limitations and the scope of the study some locomotion methodologies are not covered in this research such as snake arms, water jet propulsion methods and propelling systems. Those cases are rare in the industry and do not fully fit the purposes of the dissertation. Nevertheless, some hybrid locomotion types as well as other basic types of in-pipe locomotion are covered.

A full application of the 5-points evaluation model is essential to obtain a reliable market picture, however due to the limitation constraints the dissertation covered five different development projects for evaluation. The rest is out of the borderlines of this work.

Weight factors calculation are mainly based on the economic aspects. Due to delimitations of this work, other aspects such as ethical, environmental and social is not involved in weight factor assumptions. Nevertheless they should be covered and weight factor calculation should be developed in future works.

Also the new type of the robot concept – the ball-wheeled robot will be discussed; however, it is a first trial and evaluation of the idea of such a robot. Therefore, detailed technical survey, simulations and realizations of this novel type robot is not carried out due to the determined delimitations of this work.

2. State of the Art

From the beginning of oil industry and oil exploration till to the implementation of robotics in this industry, many different discovery and production methods have been developed to reach a higher level regarding efficiency and level of production. Besides that, also new methods have been discovered to produce not only from crude oil bases synthetic petroleum products, for example production of artificial LPG and Diesel can be good examples for those methods (Ibrahimov, 2014).

Nowadays, as well as in the near future it will be more and more important to reach higher scale of efficiency in production, exploration as well as in maintenance of oil wells or pipelines. Therefore, it is stated that, for better understanding of innovation processes it is essential to indicate the whole exploration and production steps and methods in the industry.

In a previous work (Ibrahimov, 2014) the most popular discovery methods as well as new ideas, tools or methods which are based on them have been described (Ibrahimov, 2014) and (Mayer-Gürr, 1976) figured out that there are three basic groups regarding to the most popular methods for petroleum discovery.

i. Methods those are useful in early stages as volumetric methods. The use case of this group shows up, when the borders of the oil wells are at least roughly known. Therefore, the petroleum companies have to figure out the height as well as the length of specific oil basins. Reaching a better understanding of the volume of a well, could be reached through well planned observation and after lots of experience hours.

ii. The second group of methods for petroleum discovery is applicable after a certain period of time. The oil well has to be already in usage, so that specific calculations can be derived with the gathered database to make a prediction to the future development of the oil field. For this, changes in pressure as well as balance equations of the reservoir should be available. This is useful in recovery stages of the well to adjust production rate or other relevant factors.

iii. The third group of methods gets applicable during the extension period of usage of reservoir. It is the most accurate one, because of the greater underlying database;

therefore, the forecast of the petroleum development gets more precise. For economic reasons there is a declining interest for this methods regarding to the progress in time

(Mayer-Gürr, 1976) developed another two type classification of petroleum discovery methods which is shown below and in Table 1.

a) Methods indicating the original part of oil wells reserves while the recoverable part has to be estimated. Here the volumetric and the material balance methods get used.
b) Methods indicating the recoverable part of reserves while the original reserves have to be estimated. Here the method of production decline curves gets used.

Method	**Time**	**Gives**	**Comments**
A. Static method			
1. Volumetric	Early	Oil/gas "in place"	Becomes accurate only later (when more data are available)
B. Dynamic method			
2. Material balance	Later (after 10 % of production)	Oil/gas "in place"	Requires periodic repetition
3. Decline curves	Late	Recoverable reserves	Fairly accurate
4. Pressure build-up curves	Early	Gas "in place"	Only if pressure influence reaches reservoir limit
5. Reservoir limit test	Early	Rough indication of pore volume, oil/gas "in place", reservoir radius	Useful as additional information in case of prolonged production at ± constant rates

Table 1: Reserve estimation table (Mayer-Gürr, 1976)

The estimation methods can be divided into two main parts, static and dynamic, which is shown in the table above. On the one hand, to make precise statistic calculation regarding the volumetric method the thickness, porosity, extension as well as the saturation of the underlying rock of the petroleum are necessary factors which have to be well-known. On the other hand, the dynamic methods deal with changing and balancing issues of the oil reservoir, therefore it monitors pressure or temperature as well as other factors in the production stage.

Besides, (Ibrahimov, 2014) pointed out three stages of declining phase, because petroleum is a rare energy resource a decreasing graph will show up, which can be divided in the following cases.

a) Constant percentage decline

b) Hyperbolic decline

c) Harmonious decline (Mayer-Gürr, 1976)

This declining graph is important to predict the end of usage of oil or gas fields, which gets normally calculated through economic factors in production and is not necessarily limited through the real end of the underling resource.

Besides the classical approaches in the petroleum industry, methods which cover the state of the art technology and tools become more and more important to improve efficiency. For example, as mentioned above, the first phase of petroleum production can be divided into three recoveries, namely primary, secondary and tertiary, in order to reach economic cost efficiency.

First phase of recovery is used for example for fluid displacement, which means that water gets flooded into an oil well, water and oil don´t mix and therefore a force gets generated to push the petroleum through the production system, which approximately adds 50 percent more efficiency. Therefore, half of the already generated petroleum can be produced additionally. This illustrates that primary recovery leads to a usage of the own pressure of the petroleum or other natural forces of a well and is used often for light oil grounds to lower risk and environmental factors as well as increase economic efficiency.

Second phase is often used for heavier oil wells which need in an earlier stage to apply this type of recovery than light ones. In this phase heat gets injected to the oil well to reduce its viscosity. Therefore, the oil has better material attributes which enables it to flow towards the production system. Three approaches are in use in the described thermal recovery. First of all, fire flooding, where a compressor above the ground pushes different amounts of air into the production system which leads to a controllable fire. On the one hand one issue here is that at the end coal occurs and on the other hand, that the fire consumes the oil itself which is not the best option. Another technical approach is the steam flooding, where steam is produced above the ground and instead of air injected to the reservoir. In fact, the steam reduces again the viscosity of light oil, but the problem here is that it is not capable enough for heavier oil. To solve these issues a third technique comes along where, as before, steam gets injected, now for 7 to 10 days. Afterwards the steam can cool down a bit and mix up with the petroleum inside the injection well. Out of this fact a usage for production is possible for approximately 14 days. A cycle from injecting well to production well occurs, which makes this technique unique for produce heavy oil.

As a tertiary method, the miscible flooding should be presented, which is in use after the described methods of stage one and the flooding methods of stage two. Goal is to create a homogenous but spreadable solution; therefore, miscible fluid (e.g. carbon dioxide) gets injected and mixed up with the crude oil to reduce viscosity. The effect of this method is greater, when water flooding was used before.

Very cost intense methods are the mobility ratio method as well as the microbial method, which are not used widely. (Ibrahimov, 2014)

These examples in the petroleum production process shows also the need of implementing semi- or autonomous robotic in-pipe systems for maintenance, inspection or exploration tasks to increase the overall efficiency of the petroleum industry. Since oil exists and that human being is using it, more and more tools and methods have been observed to increase efficiency in all petroleum industry parts. There is and will be always a change in state of the art tools and methods which are in use to increase efficiency in oil production, exploration and maintenance.

Few decades ago, nobody was able to imagine the enormous growth in robotic systems, which are nowadays used in the petroleum industry. Complete autonomous systems can drive or flow through pipelines and fulfill different tasks in many environmental circumstances. (Hu and Appleton, 2005)

An also very important factor for energy distribution is the transportation between the exporting countries and firms to the importing ones. So the need for a cost effective and fast transportation method arises, where the point arises where for most people pipelines come to mind, because this transportation system ensures a relatively safe and fast worldwide distribution network. Here the problem of systematic maintenance of such transportation systems occur, which in-pipe robot can do, to ensure also in the future a flexible economic system with low cost of usage.

The increasing speed in technology changes has also improved the pipeline system, which was in the end of 19^{th} century very small sized and optimized for low distances. Today there is a trend of high pressure pipelines with greater diameter and length. This boom in pipeline construction is also caused by returns on investment in a short period of time as well as ecological factors, compared to other transportation methods.

However, there is more need in improvement of methodologies and tools of petroleum industry. First of all, discovery should not be a closed-box issue for enterprises (Ibrahimov, 2014). This is where the Open Innovation and Open Source approach comes in place. Therefore, instead of other parts, more investment is needed in research and development of discovery technologies of oil reservoirs, robotic systems and open innovation. That requires improvement in geology and geophysics and a better understanding of how innovation is possible today. More accuracy can be obtained with new technologies especially with the use of telecommunication tools such as satellites, radars and other systems.

Another problem in terms of described oil recovery is the percentage of oil recovered from an oil well. The issues here are that it is very cost intense to manage the complete oil reservoir as a whole, this is why approximately only 80 percent of wells are recovered. Probably in the future also robotic systems can further improve this issue to reduce waste and improve environmental belongings and efficiency.

Petroleum recovery and extraction needs also improvements in techniques in order to increase recoverability and production rate. These improvements should be driven by leading companies and organizations with cooperation with universities and institutes. Most of oil producing countries tries to do it but in most cases it doesn't exceed the borders of individual studies or researches. Since crude oil is state property owned by governments and they are used by companies such researches and developments are characterized individually. In such cases researches are lack of experience an information changes and cannot go further than a certain limit. Such researches need to be more international and involving more parties than one or two (Ibrahimov, 2014). These facts show again the increasing need for more Open

Innovation approaches for innovation being done in the petroleum industry. This can insure with implementation of robotic systems a further increase in efficiency and raising production of the industry.

2.1 Methods of other industries

Materials or goods transported by pipelines can be divided into four groups. The first group includes oil and gas: crude oil (e.g., oleo ducts); natural gas; and refined oil products such as gasoline, aviation gasoline, diesel, liquefied natural gas (LNG), and home-heating oil. The second group includes: clean water (e.g., aqueducts); and wastewater (e.g., sewage). The third includes other industrial materials, such as: ammonia; hydrogen; carbon dioxide; and water suspensions of coal and ore (e.g., slurry pipeline). Finally, other materials are transported at a smaller scale using pipelines (e.g., beer, biofuels, etc.).

The water systems of large cities or areas are commonly a public service hosted by the government and can be categorized as a basic public service. Nevertheless, leakages and corrosion is not as dangerous as in hydrocarbon industry. Therefore, in the water industry they are not willing to invest as much as like in the petroleum industry, to prevent from a severe break and investing into error pre-detection. This means for the water suppliers that their inspection tasks cannot promise a linear quality or continuity. It is very important for this industry that an inspection system has to operate on-line without causing any shortages in the water supply, except load a robotic inspection system into a pipe.

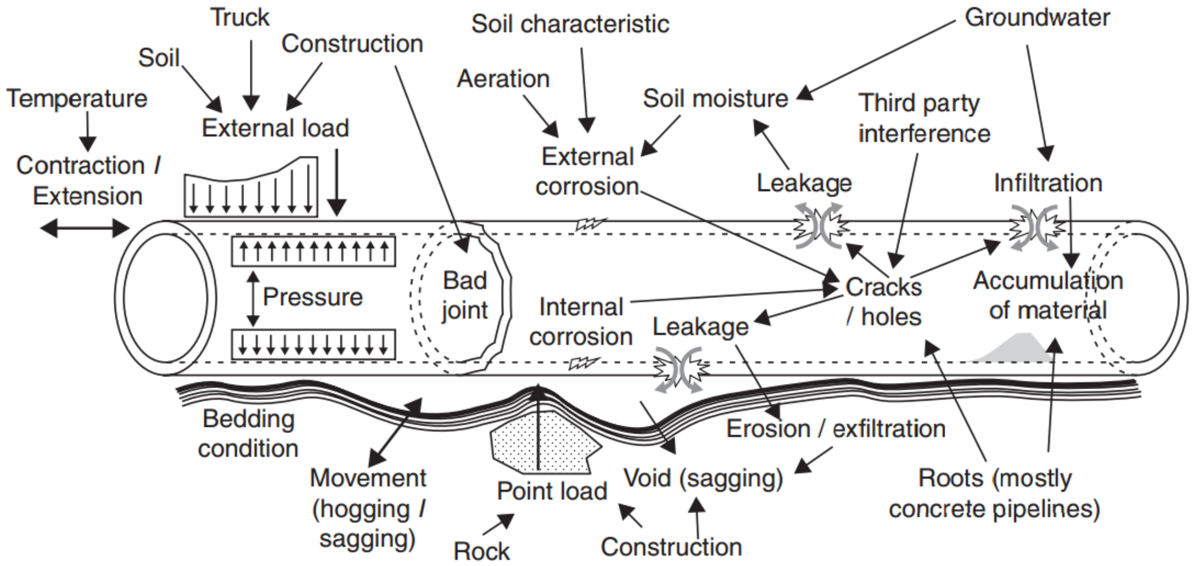


Figure 10: Pipeline degradation causes (Glisic, 2014)

Another important aim is to prevent the clear water from getting compromised, so the locomotion system of such robot has to be not erosive to avoid clouding the water with deposits. (Moraleda et al., 1999) presented a robotic system for internal inspection of water pipelines, which is able to handle smaller diameters used in urban supply networks than projects done in this industry were able to do before.

Main focus of the system is the early detection of local errors and assessment of different network sections. Through the early detection for example, cities are able to implement pipeline replacement strategies, which leads to a higher cost efficiency. As in petroleum industry, also water pipelines are not only built straight forward, so joints and branches (e.g. elbows) and special pipeline equipment are a serious issue for in pipe robotic systems.

(Moraleda et al., 1999) looked at diameters from 80 to 200 mm and a cumulative pipeline length of 2.240.305 meter over all covered service providers. The main pipeline material are pipes out of cast iron with a cement layer, in addition also steel, concrete, asbestos, cement or plastic pipelines are in use. The wide range of diameters makes it hard to develop a robotic system which can fit all these different working scenarios.

Before using pipe line detection robots, water suppliers do not concentrate on preventive action techniques, they only use corrective maintenance when an error occurs. With the visual inspections system developed from (Moraleda et al., 1999) for water pipelines as can be seen in Fig. 11, suppliers are able to become from an defensive position in an active position.

The locomotion of the whole system is handled through traction modules where the high pressure water can escape through water jets in front or backwards to generate traction force as shown in Fig. 11. The steering module which is connected right behind the camera has flexible actuators which allow changes in direction when right angles occur, but does not intend precise steering capabilities. (Moraleda et al., 1999)

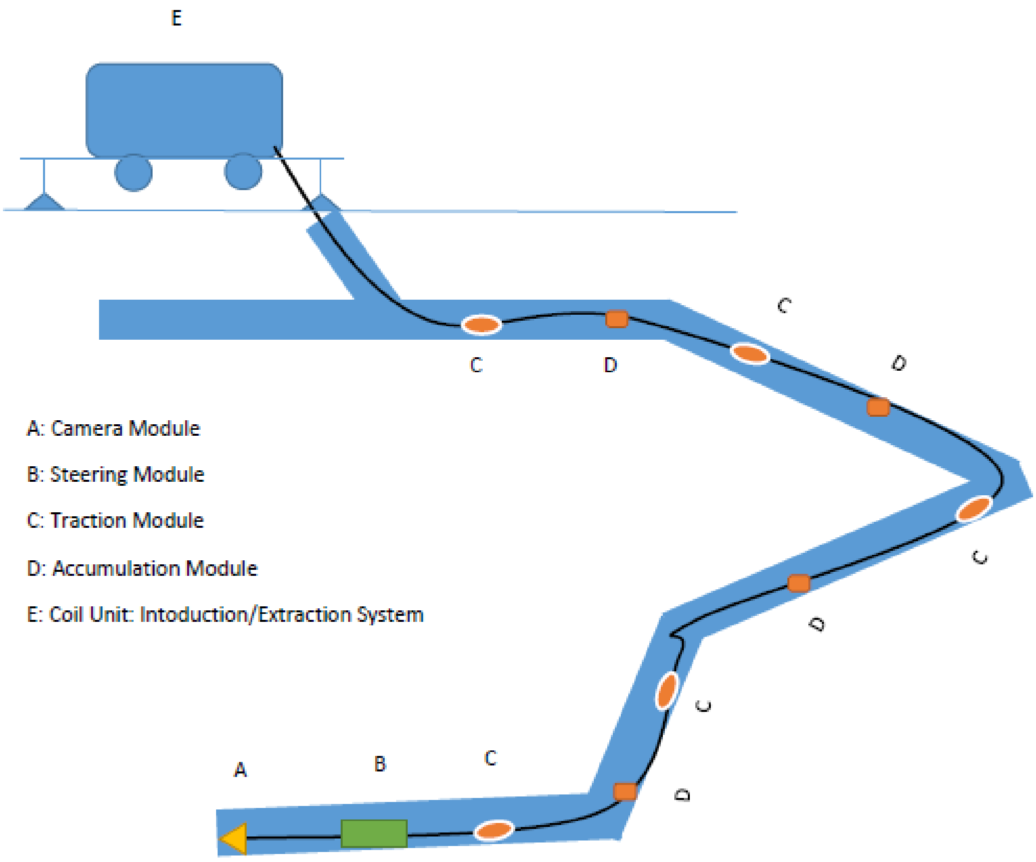


Figure 11: Visual inspection system for water pipelines (Moraleda et al., 1999)

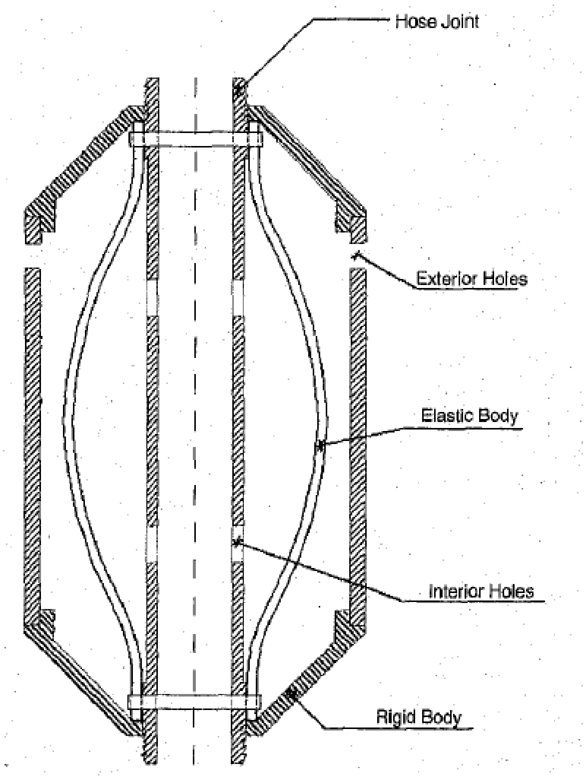


Figure 12: Accumulation module of the in-pipe inspection robot for water pipelines (Moraleda et al., 1999)

Here a difference to the petroleum industry arises, because for oil and gas pipelines it is necessary to implement capable and precise steering capabilities to overcome all sort of branches like elbows, t-branches and so on.

In Fig. 13 movement sequence with water jets has been presented. In this Figure the arrows represent the water jets. As seen, each segment moves in its turn with the tractive force of water jets. At the end the head moves in the intended direction and then the movement is finished and the loop ends. For the further movement each segment starts from the last to towards head to move by the water jets pressured water injection.

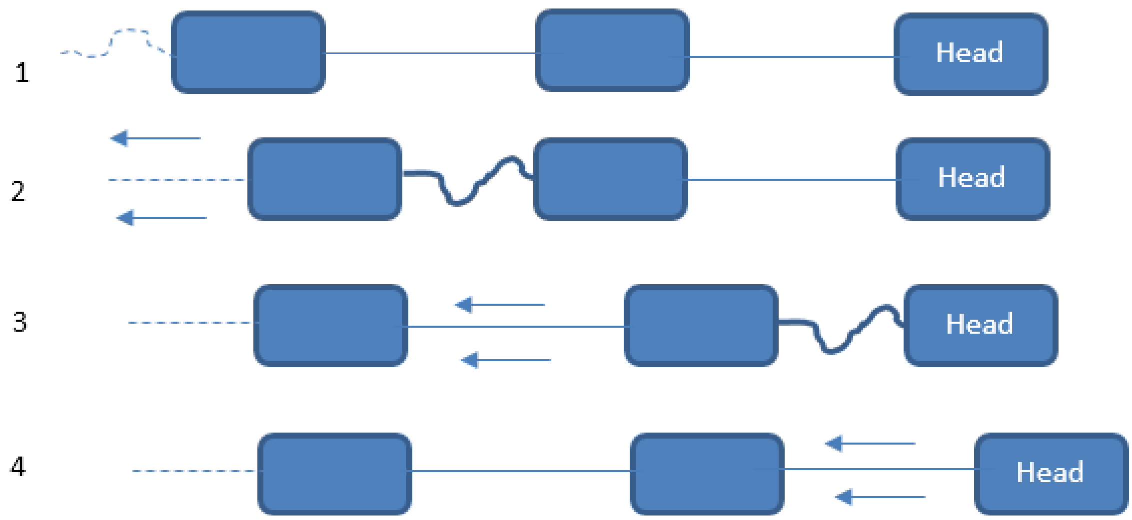


Figure 13: Movement sequence with water jets (arrows represent water jets) (Moraleda et al., 1999)

The work of (Mirats Tur and Garthwaite, 2010) sheds his lights also on robotic devices which are used for water in-pipe inspection and maintenance tasks. Main focus was the robotic application as inspection devices in water distribution networks, either for drinking or for wastewater. They found out that there are active as well as passive locomotion systems on the market for water pipeline inspection.

They reviewed a bunch of different robots like from (Nassiraei et al., 2007), which is shown in Fig. 14 and can deal with water pipe diameters from 200 to 300 mm and also overcome different types of obstacles.

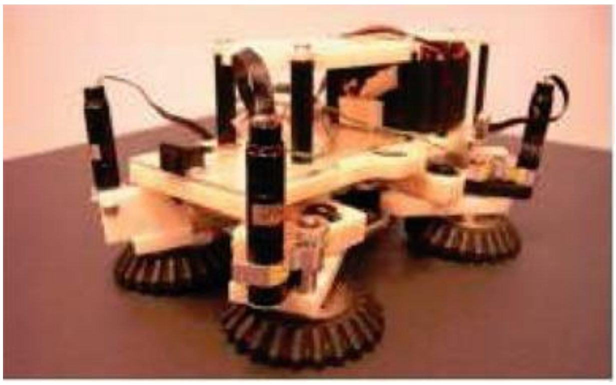


Figure 14: Kankaro robot (Nassiraei et al., 2007)

Another described approach was constructed from Optimess, which developed three different robot platforms. The KFW150, the KFW100 and the DKM inspection robot. The KFW 150 can operate in a diameter range from 150 to 800 mm and has a high resolution camera with LED illumination on board. The KFW100 can go down to a minimum diameter of 80 mm. The DKM can measure system deformation and caliber. (Mirats Tur and Garthwaite, 2010)

Figure 15: Inspection robots from Optimess for water pipe inspection (Mirats Tur and Garthwaite, 2010)

2.2 Classification and traditional evaluation of existing projects due to the locomotion type

In petroleum industry it is very common to use in-pipe robotic systems for inspection and maintenance tasks, but it is hard to find the right robot for the different requirements robots are facing in various in-pipe environments. In fact, these vehicles are used to find cracks and internal erosion problems which can occur for example from overheating or degeneration effects. (Roslin et al., 2012) as well as (Mirats Tur and Garthwaite, 2010) mentioned the common types for the locomotion part of in-pipe robots which were used in the last decades as shown in Fig. 16.

Locomotion types:	Active Locomotion	Passive Locomotion
	Wheeled	PIG (pipeline inspection gauge)
	Tracked	
	Caterpillar	
	Snaked	
	Legged	
	Screwed	
	Inchworm	

Table 2: Locomotion type overview

The pipeline inspection gauge type is a system which is moved inside the pipeline only passive through the fluid flow. In fluid filled pipelines the PIG locomotion can have also disadvantages, for example when the pressure falls under a predefined level or the robot should stop or turn in a defined area of the pipeline. (Hu and Appleton, 2005) developed a solution which gives the PIG inside the pipe the opportunity to flow within the flow direction or as well against it as shown in Fig 28. This shows how complex the solution can be only in the case of a passive locomotion system.

In general there is a distinction (Mirats Tur and Garthwaite, 2010) between passive locomotion and the active one, which means that there is any kind of drive mechanic on the robot, like wheels, legs, inchworm, tracks, caterpillars, snake parts or a screwed system. Another projection was made by (Hirose et al., 1999), they divided the possible locomotion types of in-pipe inspections robots into three general forms. Form 1 robots are using the pressure of the fluid inside a pipeline, Form 2 transfers the propulsion through an elastic rod and as described before Form 3 has any kind of drive mechanism on it, seen in Fig. 15.

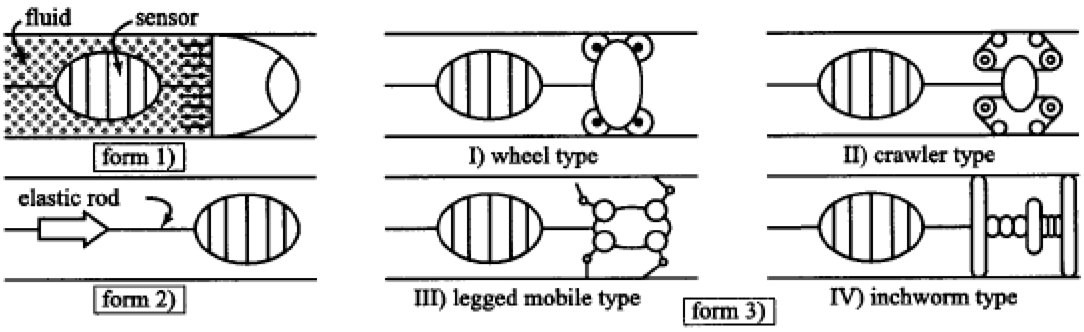


Figure 16: General Forms 1-3 (Hirose et al., 1999)

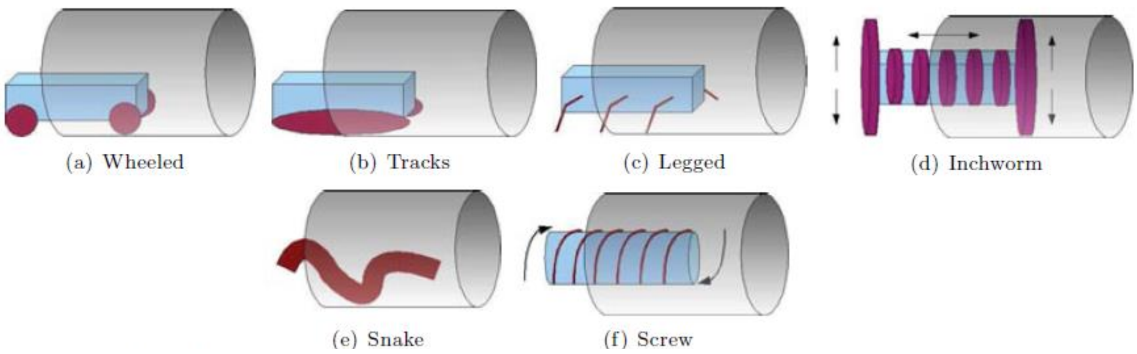


Figure 17: Selective active locomotion types (Mirats Tur and Garthwaite, 2010)

The wheeled type, for example used by (Choi and Ryew, 2002), (Scholl et al., 2000), (Suzumori et al., 1998) or (Okada and Kanade, 1987) for their robots, is used in common when there are branches along the pipeline, because it can counter this limitation with its differential driving ability. Other researchers like (Roman et al., 1993), (Roßmann T. and Pfeiffer F., 1996) or (Neubauer W., 1994) improved the legged type to meet the defined requirements for acting in the working environment. These different pipeline configurations make it necessary to find new ways to assess all the requirements for the working environment, which is more and more done by combining the established locomotion types. (Roslin et al., 2012)

As already mentioned above, these different locomotion approaches have been developed for different cases, working environments and distinctive competencies and not to be applicable for all purposes. In the next subchapters different locomotion developments of past research are covered to show an overview of the ongoing scientific development in this area.

2.2.1 Caterpillar type Locomotion

(Park et al., 2009) constructed a robot called, “Pipe Adaptive Robot of YonSei University”, short Paroys-II, which can actively adapt to changes in the pipe diameter. The robot can handle pipelines with diameters from 400 mm to 700 mm. The robot consists out of a main module in its center and three pantograph mechanisms which are mounted on it as shown in Fig. 17. The pantograph mechanism allows the robot to adapt in diameter changes and its driving capability is solved due to the assignment of tracks which are connected to the pantographs in order to keep contact with the surface inside the pipeline. These track modules are connected with an active joint with structural compliance.

This caterpillar type shows how important it is for robotic locomotion design to take the size of the objective pipe into account. In fact, it is very common that in petroleum industry the robots have to face different and changing pipe diameters. Before (Park et al., 2009) constructed their Paroys-II also other projections for this problem have been developed. They have used springs as elastic components to ensure that the driving mechanism has enough force to push the caterpillars to the pipe hull. The drawback here is that this locomotion system can only adapt to very small diameter changes and therefore can lead to a loss in flexibility of the whole robotic system. Another solution to this problem is to use passive linkage types called DCAMs which allow the robot to reach more freedom in case of diameter change.

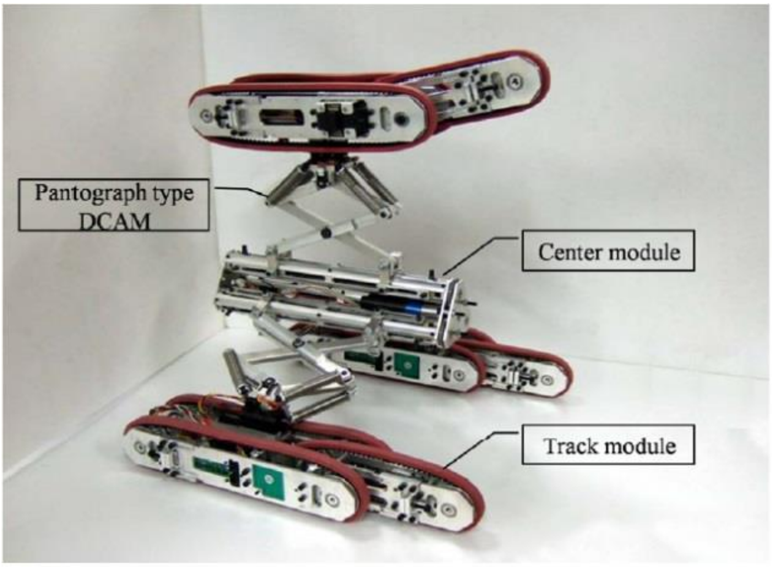


Figure 18: Overview of Paroys-II (Park et al., 2009)

In their paper (Park et al., 2009) used as main variables the length of the pipeline L, radius of the pipeline R, power supply PS as well as the communication variable COM.

In an additional paper from 2011 (Park et al., 2011) discussed different geometrical shapes of in-pipe robots regarding to the slope angle of pipelines to ground Ø (is explained in Chapter 3). In fact, they divided the ability of robots to adapt to diameter changes in two parts, either active or passive. The passive solution, as already described in their last paper from 2009, uses linkage structures and elastic components like springs to push their locomotion part against the pipe wall. The passive method to diameter changes has the advantage, that there is no need to consider the independent control of the normal force as well as the ability to fulfill smooth changes in the diameter, but as stated above, the problem is the small range the robots are able to react to diameter variations and the lack to correct the normal force when needed. Active solutions as the other part are able to react to the normal force but are more complicated in the design process of a locomotion system. To share the advantages of the two approaches many engineers use passive components in their active systems. On the other hand, there are robots which need no active systems to adapt to little changes in the diameter of a pipeline. For example, Inchworm-type robots can execute this task or robots which use magnetic wheels can hold its body on steel pipelines without additional mechanisms.

Fig. 19 shows the described Paroys-II developed by (Park et al., 2011) in an inclined pipeline. The robot can react to changes in the slope of the pipeline with the help of active and partially passive parts as well to changes in pipe diameter.

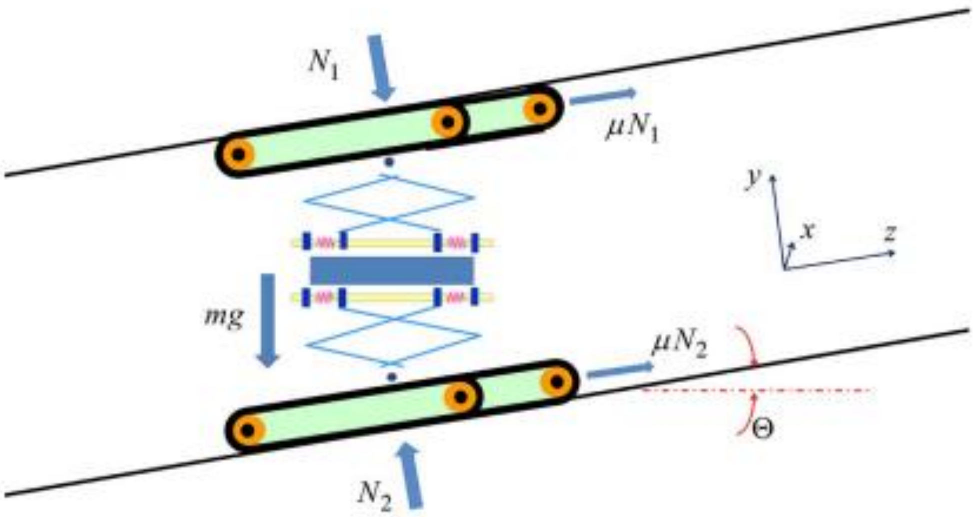


Figure 19: Body diagram of Paroys-II in an sloped pipeline (Park et al., 2011)

This shows the problem that there is a need to handle different amounts of normal force (according to the developed variable set, N1 gravity force indicated in Chapter 3) regarding to the slope of the pipeline Ø. Another problem of steeper slopes of a pipeline is the rising need for efficiency and energy consumption and often not the motion part itself. This all relies to the variable I_g (explained in Chapter 3), the weight use factor of a robot, which means that a heavier robot needs more power to climb greater angles between the ground and the pipe wall for slipping down prevention. (Park et al., 2011) argues that if a robot cannot react to changing slope angles it should maintain a constant normal force in the working environment inside the pipeline and take the drawback of raising energy consumption. Paroys-II is able to react to different gravity forces and therefore can save energy through its force control system which is responsive to slope changes of the pipeline and reduces the force when needed.

Another important obstacle and therefore a challenge for the robot's locomotion system inside a pipeline are curves or branches. This fact also minimizes the clearance of the body size (regarding to the variable RR, radius of the robot).

(Kwon and Yi, 2012) developed an in-pipe inspection robot which is able to serve in 80 mm to 100 mm diameter pipelines and consists out of two modules which are linked through a compression string. One problem what such robots can face is that they can be only manually controlled, but there are some which are semiautonomous or complete autonomous systems. For pipelines with small diameter (Choi and Ryew, 2002) constructed a semiautonomous robot, for larger diameters ranging from 200 mm to 300 mm, (Nassiraei et al., 2007) built a autonomous system for in-pipe inspection.

In addition to this approach, (Rome et al., 1999) have also built a test system for inspection of 300 mm to 600 mm sewer pipes. However, (Kim et al., 2010) developed these robots a step further, because the stated systems above are only capable for simple curved or horizontal pipeline settings. Their performance in overcoming Y- or T-branches is often not as good as in straight pipelines, because of inefficient robot design in terms of space (regarding to the radius of the robot, RR) and adhesion coefficient problems.

(Kim et al., 2010) invented the FAMPER robot which is capable for the examination of 150 mm diameter pipelines and has the power to overcome T- and Y-Branches as well as 45 or 90 degree elbows. To fulfill these specifications, the robot's radius is very small and customizable. This leads to high cost and steering efficiency. The locomotion design of FAMPER uses four instead of three caterpillar units, therefore it is able to contact with at least three units to the pipe wall which gives the robot the above described ability to overcome branches and elbows.

In fact, the possibility that the robot loses contact to the pipe wall exists also with four caterpillars but these cases are extremely rare. This means that the robot needs the ability to adjust its own position to ensure that at least three caterpillars have wall contact. To overcome this locomotion singularity issue (Kim et al., 2010) designed two caterpillar locomotion types. The first type uses caterpillars which are sloped in a 5-degree angle regarding to the robot chassis instead of using a linear slope. Tests with this kind of locomotion type showed good performance in overcoming the singularity issue and self-adjusting its own position with respect to the pipe wall in contrast to a linear one. This goal gets achieved with the spiral motion generated by the shifted caterpillars. For the second type (Kim et al., 2010) constructed a flexible caterpillar system which consist out of three parts. The main frame, the front as well as the middle part are flexible till 60 degrees and have a 30-degree branch which allows the locomotion system to overcome obstacles and improves turning capability.

Fig. 20 demonstrates the features of the caterpillars of FAMPER inside a pipeline.

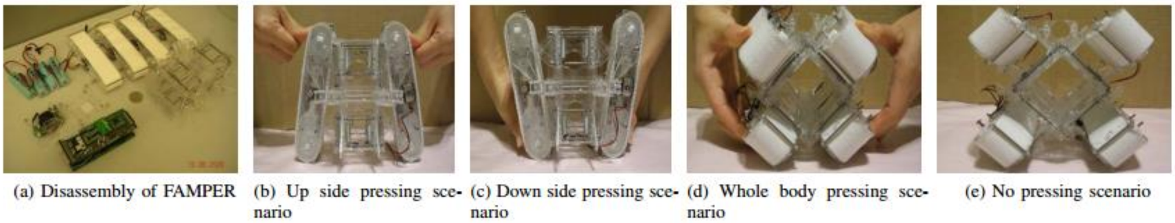


Figure 20: Famper´s disassembly and features of links and suspensions (Kim et al., 2010)

Another approach developed by (Kwon et al., 2011) is a caterpillar-based in-pipe robot which can be used for diameters ranging from 80 mm to 100 mm in an indoor environment. The unique locomotion feature of the robot are the shifted caterpillar wheels and the connection of two robot modules with springs, which allows the vehicle to navigate better through pipe branches. Regular wheel-based robots often can’t manage T-branches or elbows. Out of this fact the authors connected two parts together to overcome the problem that the robot gets stuck in T-branches, which can occur when only one part is used, similar to the problem discussed above. The robot consists out of two modules connected by a compressive spring. Each module has a main body, three linkage structures and three caterpillar wheels.

Fig. 21 and Fig. 22 show the two robot modules as well as the main specifications. (Kwon et al., 2011) used 13 out of 26 variables from the predefined set of variables in Chapter 3.

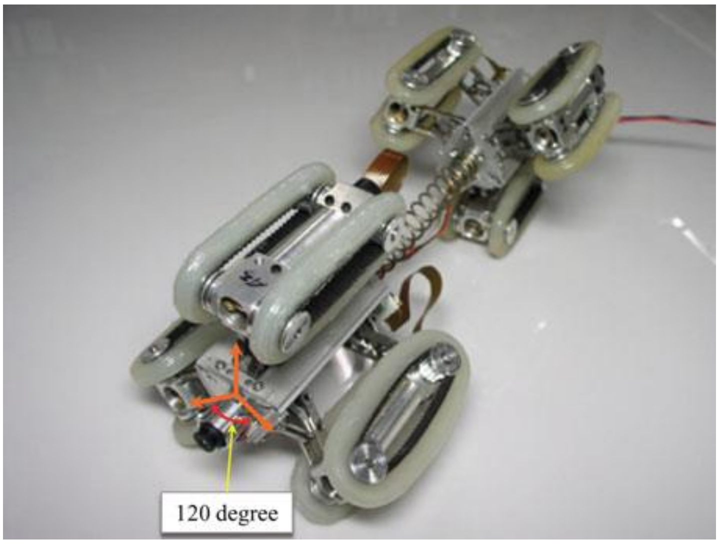


Figure 21: Caterpillar based pipe robot (Kwon et al., 2011)

Specification	Value
Weight of each robot module	266 g
Motor diameter	10 mm
Length of the robot module	78 mm
Total length of the robot	230 mm
Exterior diameter	80-100 mm
Max traction force of the robot module	1.183 Nm
Linear speed	5.5 cm/sec
Max. speed	9 cm/sec
Camera and sensor module length	18 mm
Serial communication distance	15 M

Figure 22: Specifications of in-pipe robot developed by (Kwon et al., 2011)

2.2.2 Clamping, inchworm, snake or PIG-Type locomotion

The clamping locomotion system gets described in (Roman et al., 1993) from 1993 and is shown in Fig. 23. One clamp connects to the pipe wall and another one gets released, the robot extends itself in this case in a range from 1 to 5 inch. Then the front clamp engages again with the wall and the rear clamp gets released and the robot moves forward. Another version of this kind of robotic locomotion design was introduced by (Okamoto et al., 1999), they developed in 1999 a new robot for the Brazilian petroleum company Petrobras. Their research focus was a vehicle that can overcome pipelines with a diameter range from 200 mm to 500 mm as well as lengths of more than hundred kilometers. From the variable side they only discussed the length of the pipeline, the diameter and robot's radius. The developed schematic of the robot is shown in Fig. 24.

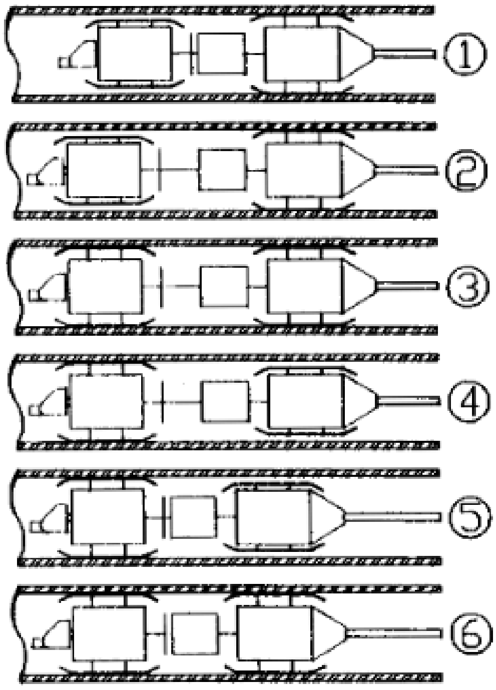


Figure 23: Clamping locomotion (Roman et al., 1993)

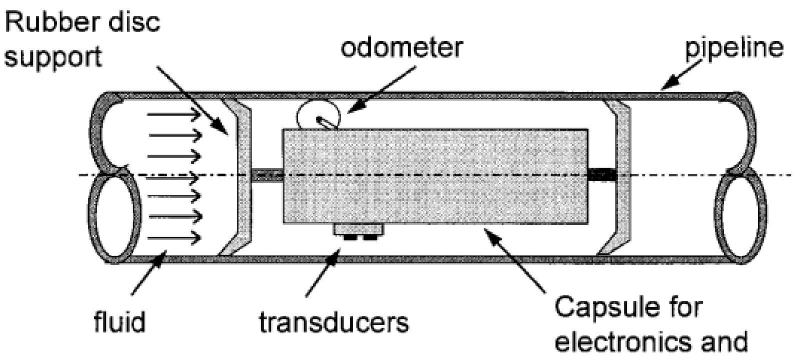


Figure 24: Robot schematic developed by (Okamoto et al., 1999)

(Bertetto and Ruggiu, 2001) discussed in their paper an in-pipe robot developed by (Fukuda et al., 1989) called Mark2, which consists out of three elements which were connected through the application of rubber actuators and powered by a hydrogen storage composition. Four bent actuators make sure that the robot is not losing grip during operation and are pressed onto the pipe wall.

As main variables (Lu et al., 2009) focused on diameter, physical properties of the robot itself as well as on the control system, when they designed a robot which uses electromagnetic linear actuators. They discussed the improvement capabilities of further research in matters of actuators and energy source. They figured out, that the robot which is in the literature often called as inchworm robot shows good movement skills combined with needed output force.

The design consists mainly out of two parts; the first one is an actuator which can crimp in the direction of movement as well as the second component namely clamps or grippers which are used to gain friction against the pipe wall. In fact it uses the same principle which was already introduced by (Roman et al., 1993) discussed above. Fig. 25 shows the operation cycle of an inchworm robot.

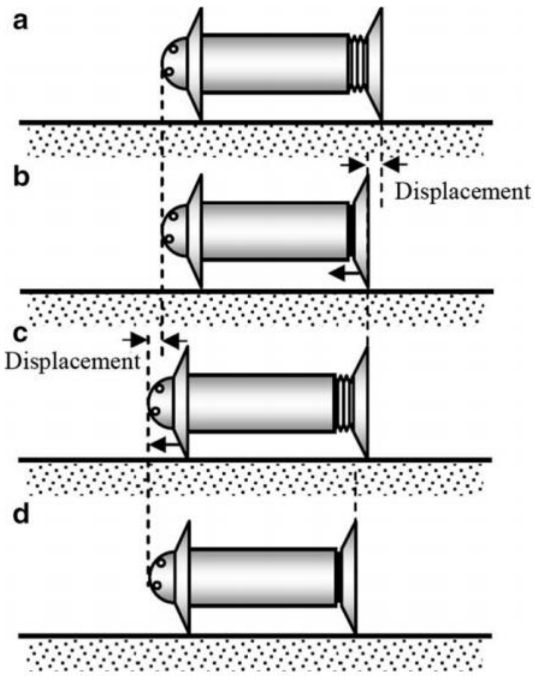


Figure 25: Inchworm robot operation cycle (Lu et al., 2009)

In addition to (Lu et al., 2009) also (Lim et al., 2008) focused on research regarding the inchworm type. Their focus lies mainly on small pipeline diameters up to half of an inch, which leads to a pneumatic line-based micro robot, with no pneumatic lines in the body itself. Their locomotion system is based upon differences in the size of the holes of the robot chambers, which leads to a delay in the airflow which is pushed through the different components. They looked at the velocity which is linked to the change of the sizes of the holes between the extension module and the tail of the inchworm under different pressure conditions.

In many passes they figured out a hole in size of 0.8 mm between two chambers, but they faced a repetition problem to maintain a constant velocity. Their final score was to show the direct influence of the void size on the locomotion speed performance, which can be controlled by disposed pressure and cycle time. In the end they constructed a prototype which is able to move in a pipe with a diameter of 16 mm, a velocity of 55 mm/s under 2 bar pressure and a cycle time of 0.6 s (Lu et al., 2009).

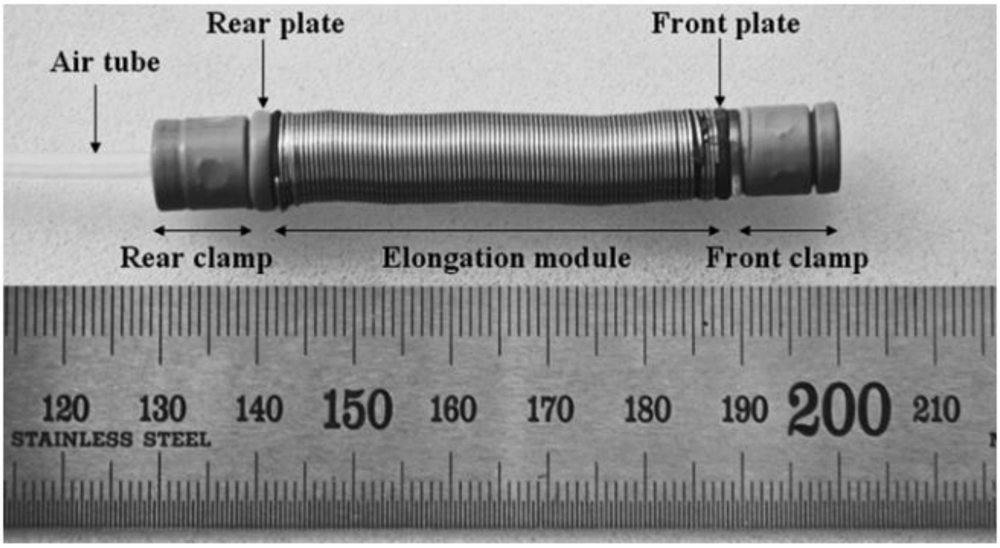


Figure 26: Inchworm prototype developed by (Lim et al., 2008)

The paper shows also a starting point regarding maintenance power of inchworm in-pipe robots in the use case of small pipe diameters.

(Kuwada et al., 2006) realized a snake like locomotion system, which is able to operate in changing pipe diameters from 36 mm to 180 mm as well as in T-branches and vertical pipeline settings. The robot itself is formed out of thirteen serial combined links, where each link is equipped with an actuator. With this combination of serial links with actuators, they were able on the one hand to reduce the number of wirings from 72 to 6 to gain on the other hand more robustness against electrical interferences.

In addition (Kuwada et al., 2006) raised their adhesion coefficient μ between the links and the pipe wall by an increase of the amplitude reference and a decrease in the wave length, to ensure that the snake in pipe robot is now able to move in vertical direction with a velocity of

3.9 mm/sec in 55 mm diameter pipelines. The maximum velocity the robot can reach in a vertical position under perfect conditions lies by 5.9 mm/sec. The driving principle of the constructed snake in pipe robot is shown in Fig. 26.

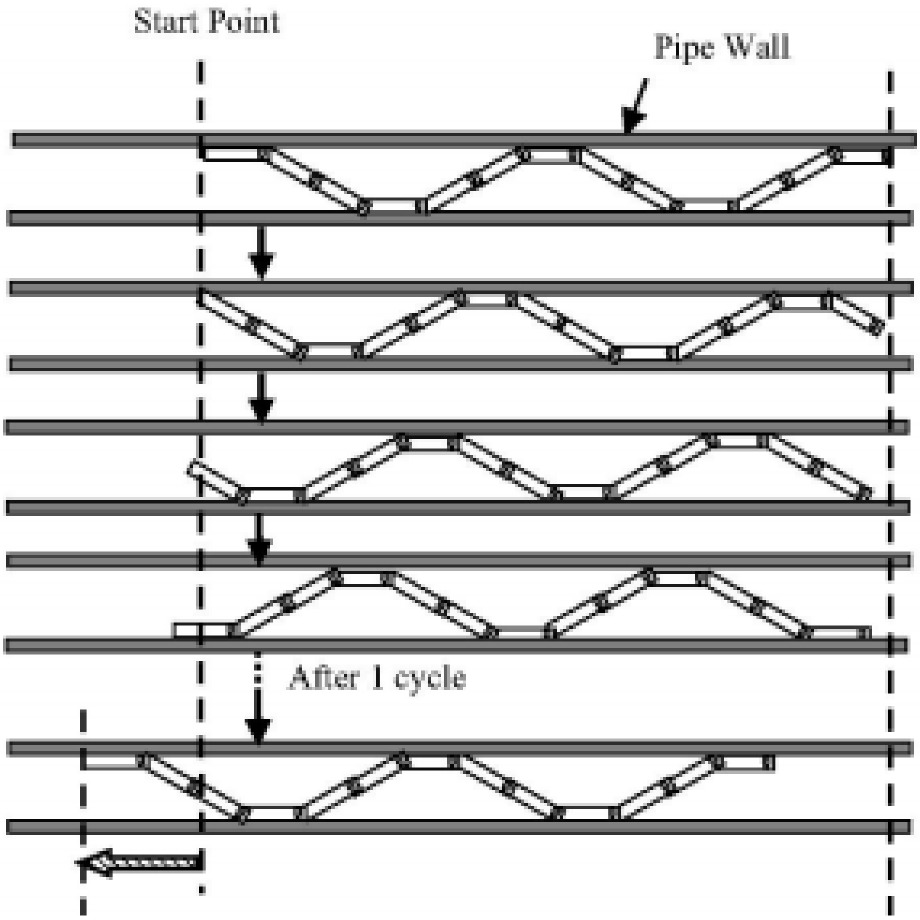


Figure 27: Driving principle of snake robot (Kuwada et al., 2006)

Another worm approach was constructed by (Ono and Kato, 2010) and is used for pipe diameters of 78 mm, but can move a pipe length (L) of 32 meters. It uses rubber bellows as actuators and sixteen rubber rings are mounted to sustain the friction force F_f. The force balance of the robot is shown in Fig. 27.

(Hu and Appleton, 2005) discussed a locomotion type, which gets often mentioned in the literature as PIG or double screw type motion. The PIG approach was developed to overcome difficulties of other robotic locomotion approaches. For example, on the one hand for wheeled in pipe robots it can be a very difficult task to gain enough traction force (F_t) to move against the velocity flow of the fluid inside the pipeline Φ_f. On the other hand, locomotion systems with legs are often hard to control and can show a poor proportion between their weight use factor I_g and their capacity to carry a payload m.

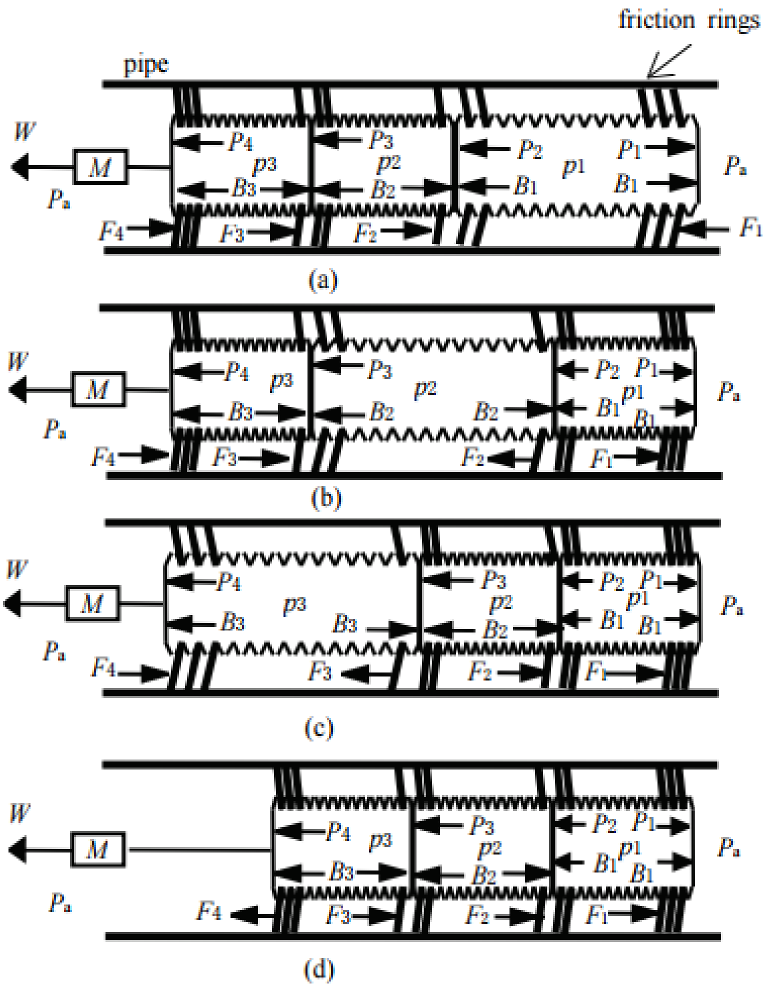


Figure 28: Force balance of micro robot developed by a,b,c,d) movement sequences (Ono and Kato, 2010)

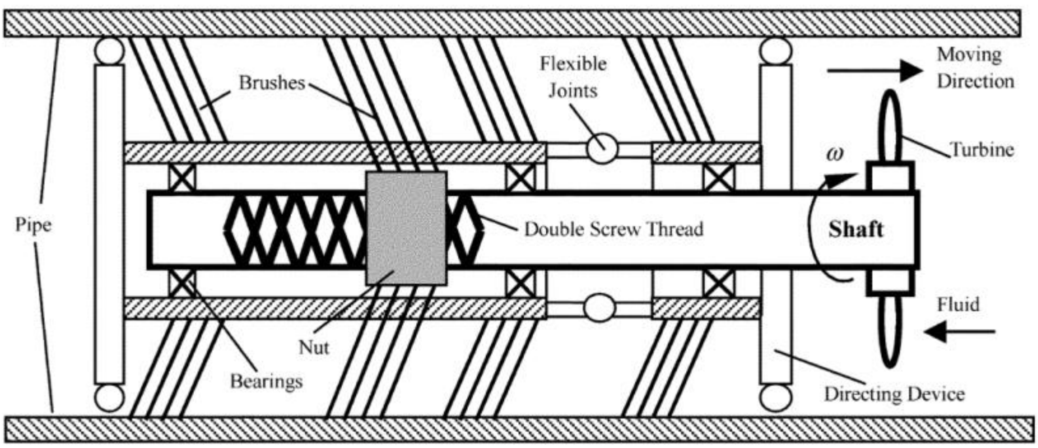


Figure 29: Basis structure of a self-drive pig (Hu and Appleton, 2005)

In the case of the PIG locomotion the fluid flows through the turbine and affected by the shape of the used blade, which (Hu and Appleton, 2005) take as a constant variable. Out of the rotating turbine a thrust force F_d is generated which moves the robot in working direction. The basic structure of a self-drive PIG is shown in Fig. 29.

2.2.3 Crawling or spider type locomotion

In 1994, (Neubauer W., 1994) was one of the first authors who described a spider type robot for in-pipe locomotion. The main goal was to overcome all sort of branches, junctions, steps or corners which can occur in the inner setting of a pipeline. In previous research (Neubauer W., 1994) was not able to find a lot of robots with such prerequisites, because in the early 1990 many approaches have strong limitations regarding to radius of the pipeline R, or the slope angle from the pipeline itself to the ground Ø. (Neubauer W., 1994) mentioned the approach from (Madhani and Dubowsky, 1992), because they used three legs to climb two ladders and the control systems was able to plan the further movement of the robot in know areas of operation. (Neubauer W., 1994) described in his paper a robot with legs which pushes against the pipeline wall for further movement, which is shown in Fig. 30.

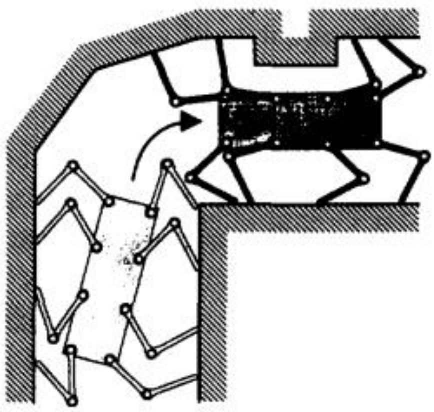


Figure 30: Simulation of legged pipe robot (Neubauer W., 1994)

In their paper (Galvez et al., 2001) discussed the TUM robot, which uses its crawlers to connect direct to the pipe wall, in fact their measurements are based on a tactile foot sensing system. The main task of the paper is to discuss the forces which are needed to gain contact to the pipeline wall. The robot uses a five axis force and torque sensor which is called intrinsic contact sensor and was mentioned in the literature before by (Bicchi et al., 1993). In 2001 (Galvez et al., 2001) were the first scientists who implemented such force based sensor into a robot.

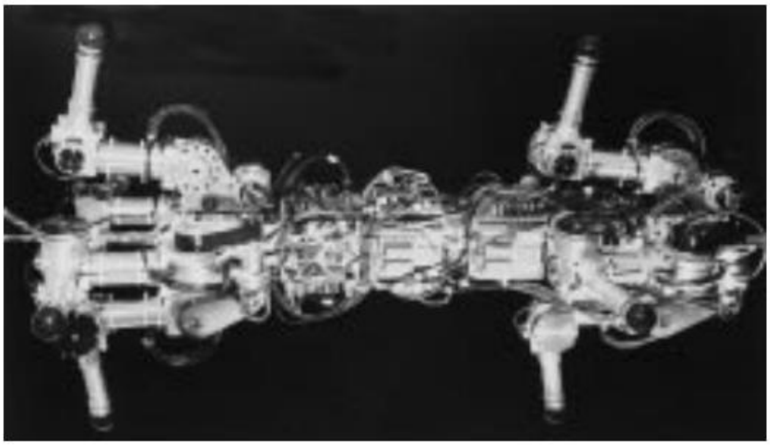


Figure 31: TUM crawling robot (Galvez et al., 2001)

(Zagler and Pfeiffer, 2003) invented an in-pipe crawling robot, called MORITZ. The main focus of this robot is to enhance locomotion capabilities to overcome pipeline branches. For the determination of the load (regarding to I_g of the presented variable set) they first tweaked the feet forces of the crawler with linear programming and under different constraints. The first constraint they take under account is that the target position has to be observed, second constraint relies on the friction force where after linear programming for the friction cone a friction pyramid has to show up, another one sets a limit for the foot force of 350 N. (Zagler and Pfeiffer, 2003) argue that all these constraints are essential due to the implemented force sensors. In addition to the mentioned constraints and to make the robot able climbing through pipeline branches, they faced issues regarding the implementation of the locomotion system itself. (Zagler and Pfeiffer, 2003) analyzed the gait pattern, the joint angle limitation as well as the length of their crawler legs to make sure that the robot is able to move through branches of a pipeline. In the end they added two bending joints and two rotation joints to the formal design of the central unit.

Now the central unit is divided into three parts, the front and rear body, where the legs are mounted and the middle body. This locomotion design insures that the robot is able to bend its main unit and to move well inside pipe branches.

2.2.4 Wheeled type locomotion

(Sato et al., 2011) reviewed a lot of different robotic locomotion approaches and ended up with a unit based wheel robot which is suitable for in-pipe inspection and can overcome branches and elbows depending on the number of units. The system itself consists out of units which are connected through links with each other. One unit body is made up of wheels, timing belts, pulleys and actuators. The weight of such unit lies by 613 g with a width of 69 mm, a height of 90 mm and a length of 174 mm. For locomotion the robot uses two DC motors, which are implemented in the wheels for moving forward or backward, as well as two RC servo motors, which are needed to push the links in both sides of the pipe wall. When robots task is to move in a horizontal pipeline three or more units getting linked, for the movement in braches or elbows or a different pipe diameter the number of used units change (regarding to the number of bodies, $\#_B$ of the presented variable set in Chapter 3), as shown in Fig. 32.

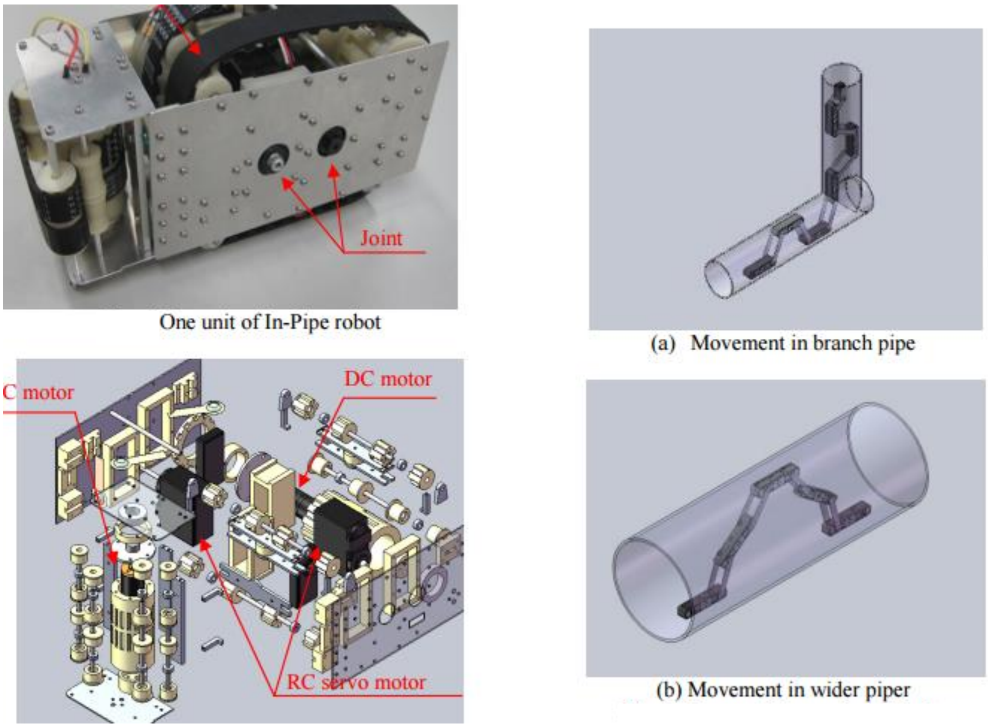


Figure 32: In-pipe robot unit (Sato et al., 2011)

In the work of (Suzumori et al., 1998) a wheel based micro inspection robot is covered which was developed in the Toshiba laboratories. The singularity of the robot is the one-motor-actuated three wheels in triangle shape which is shown in Fig. 33. The linking part in the middle is able to adapt actively when needed. From variable side only the diameter and other physical properties were discussed.

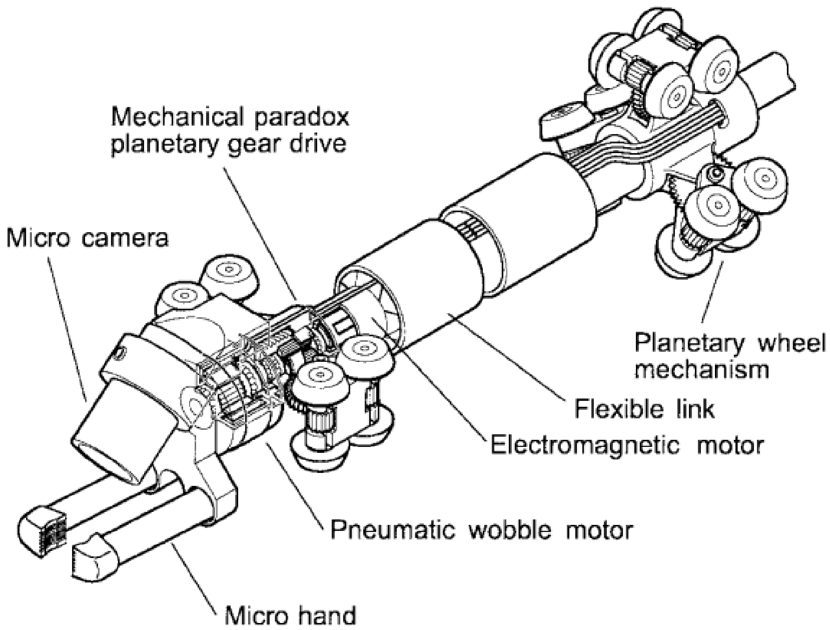


Figure 33: Configuration of micro inspection robot (Suzumori et al., 1998)

(Hirose et al., 1999) constructed the Thes I-IV inspection robot series and introduced the concept of “whole stem drive” allowing the in pipe inspection robot to move further in long pipeline settings, which is shown in Fig. 34.

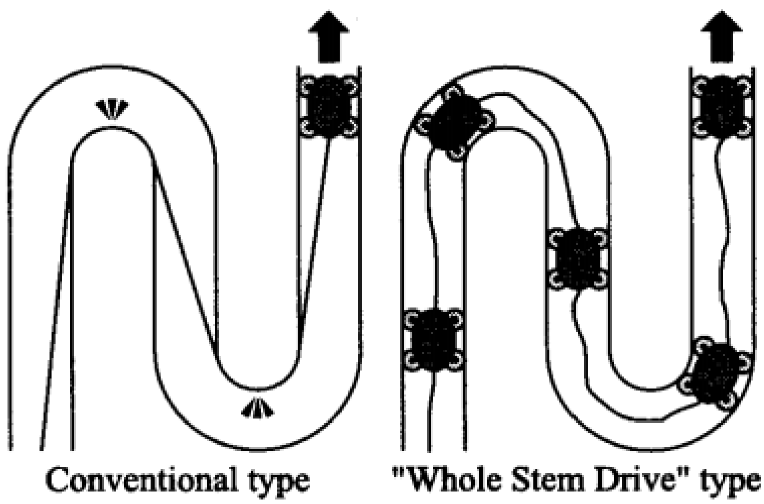


Figure 34: Whole Stem Drive (Hirose et al., 1999)

All four in pipe inspection robots discussed by (Hirose et al., 1999) were constructed for different pipeline diameters from 25 mm, 50 mm to 150 mm. They figured out three main classifications, first of all forms with utilize the fluid pressure like PIGs, second forms with transfer the driving force through an elastic rod and as last one, forms which have a built-in drive mechanism. (Hirose et al., 1999) divided the third main classification again into crawler type, legged mobile type and inchworm type.

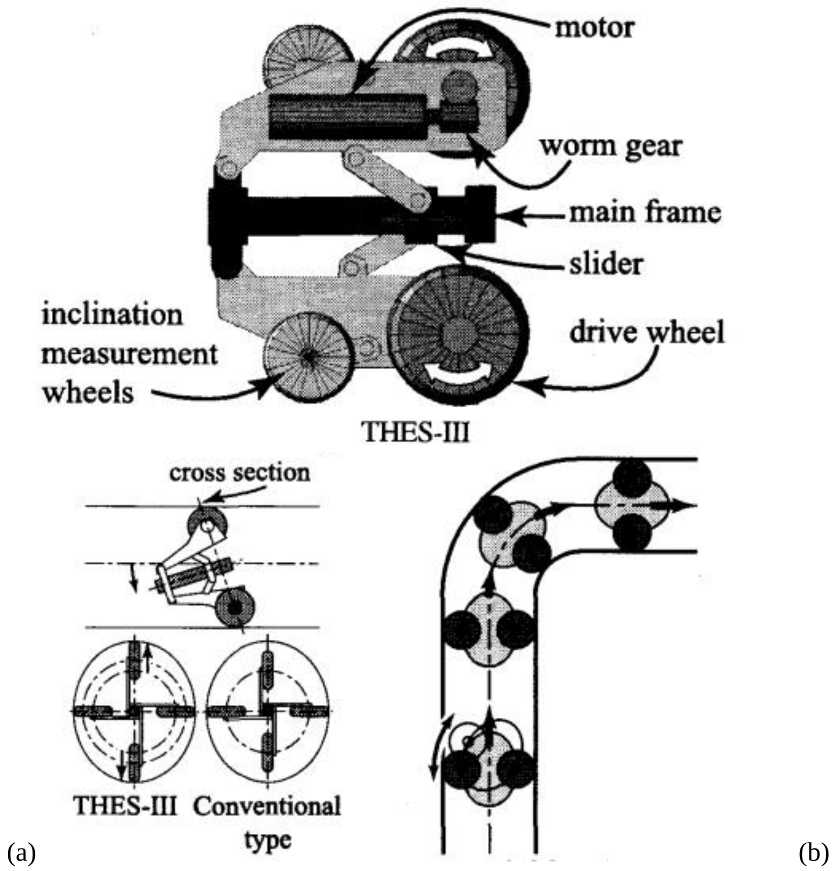


Figure 35: Thes-III (above), a)Independent two links; b) Control Configured Vehicle (Hirose et al., 1999)

(Horodinca et al., 2002) presented in their work two wheeled in pipe robots which are able to serve a diameter range from 40 mm to 170 mm. Aim of the construction was to reduce the overall complexity and gain mobility trough the usage of a single actuator. They are using a two-body or a three-body design regarding to the needed pipe diameter, which is shown in Fig. 36.

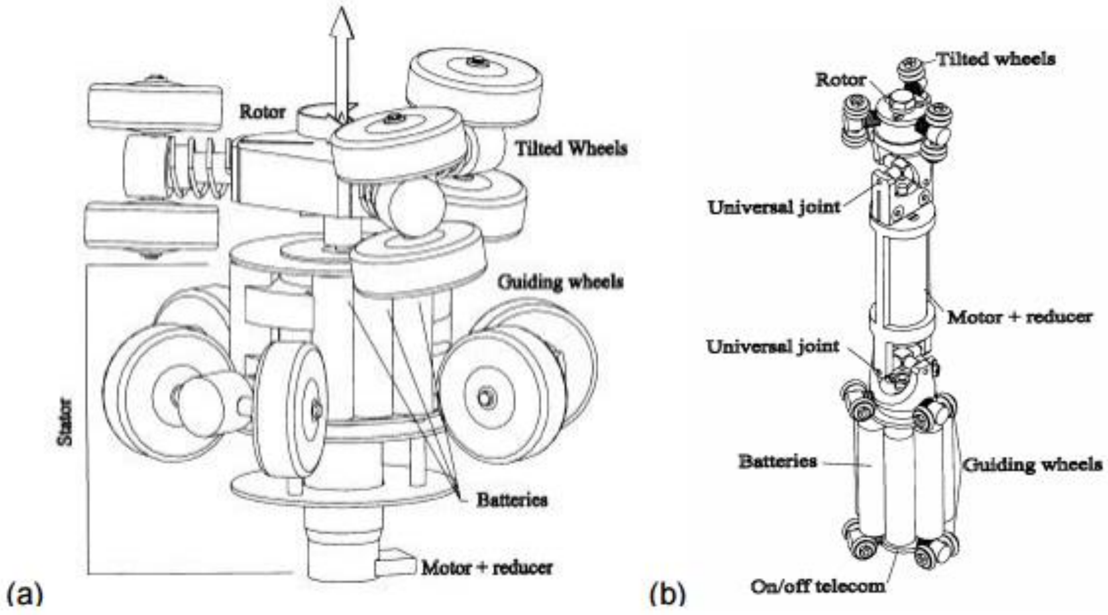


Figure 36: Robot architecture a)Head b) Whole body developed by (Horodinca et al., 2002)

(Oya and Okada, 2005) pointed out that for a wheeled robot it is a very crucial task to overcome obstacles inside a pipeline, so there is a need for developing robust and effective steering capabilities. In their paper they present a sketch of a robot structure which should fulfill this task.

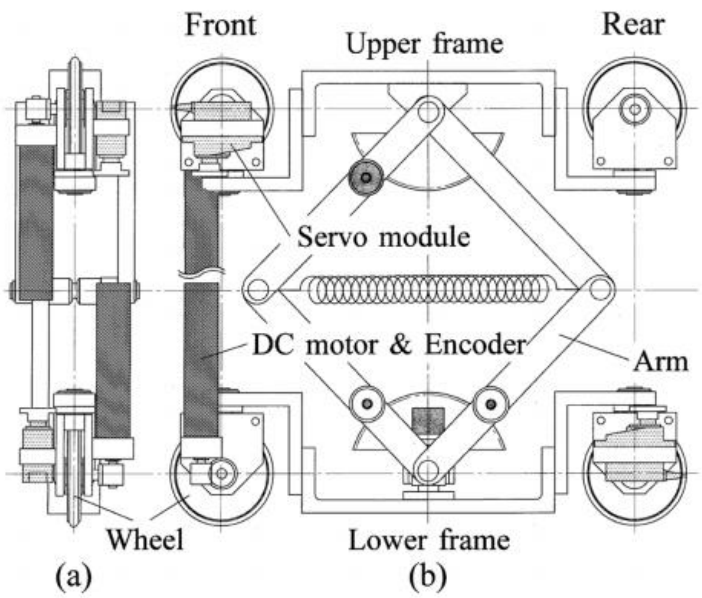


Figure 37: Steerable, wheel-type, in-pipe robot structure a) front and b) side views, developed by (Oya and Okada, 2005)

(Zhang and Yan, 2007) invented also a wheeled in pipe locomotion system which is able to adjust to pipe diameters from 400 mm to 650 mm. In addition, the robot brings a constant tractive force Ft output with an adjustment capability. Goal of this robot is to inspect pipelines for cracks and corrosion or to measure the wall thickness. The maximal pipeline length (L) the robot can operate is set to 1 km.

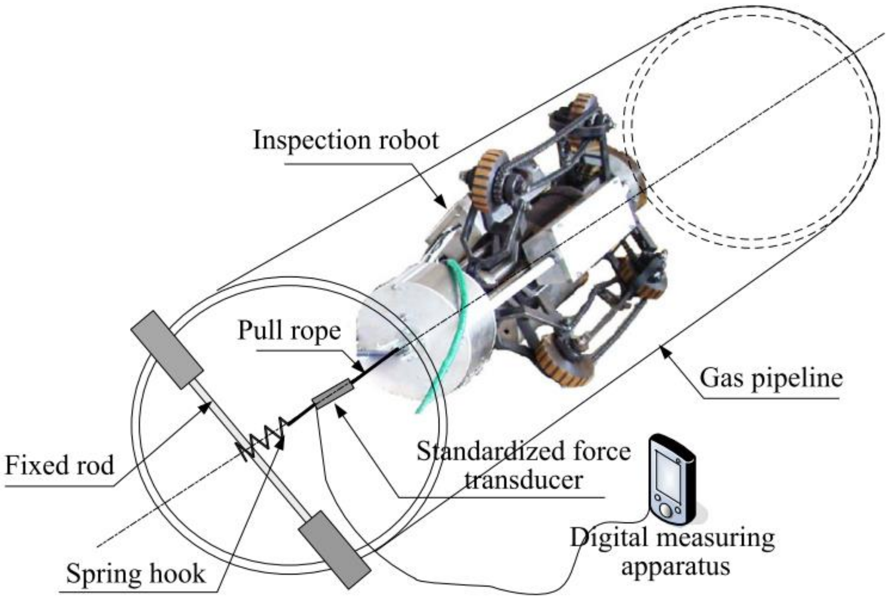


Figure 38: Tractive force adjusting (Zhang and Yan, 2007)

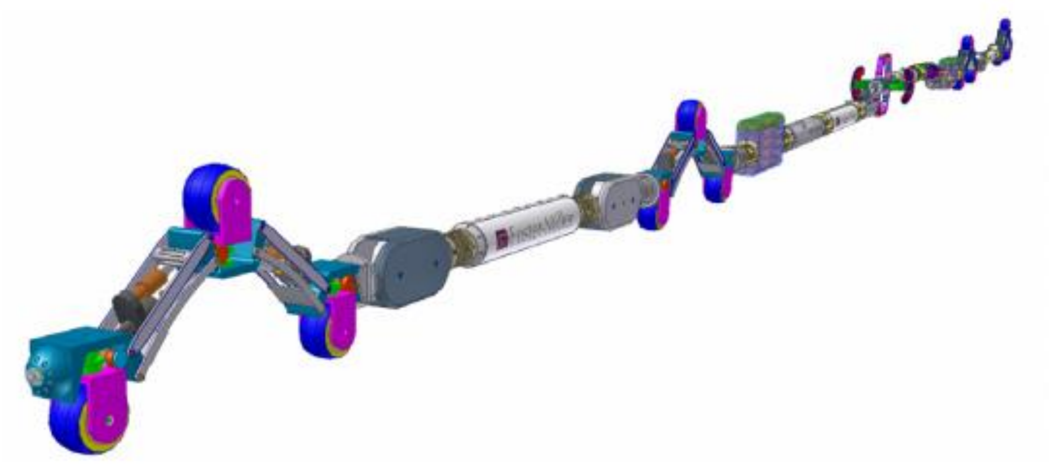


Figure 39: RoboScan robot for unpiggable pipelines (Vradis, 2004)

(Vradis, 2004) worked on the problem that in many cases the PIG locomotion for in pipe robots is not possible, because of obstacles with can occur inside pipelines. These obstacles can be 90-degree bends or elbows as well as diameter changes at pipe connections. To solve this issue, they invented RoboScan, which was developed out of their previous work, the pipe mouse robot. RoboScan is able to operate forward as well as backward (regarding to the introduced variable M – movement direction of the variable set) in pipelines from 100 mm to 150 mm. The locomotion force (F_t tractive force and F_d thrust force is explained in the next Chapter) is done by two tractors, one in front and one in the rear section of the vehicle. Each tractor consists of two tripods and an electronic module.

Also (Kwon et al., 2011) worked at the problem of obstacles like branches inside or vertical pipelines. As already seen, many locomotion systems have been developed to overcome such type of issue. A very common approach in the literature is the usage of differential drive mechanisms, which has usually mounted three powered wheel chains; the problem is that when the vehicle is passing obstacles sometimes singular motion can occur.

To encounter this problem active steering joint methods or the combination of several bodies ($\#_B$) have been developed. In fact, at the end of planning process the problem of too much weight (I_g) and size (R_R robot's radius) can occur. (Kwon et al., 2011) stated that an additional problem when using a three-wheeled chain system is that the space for mounting sensors can be very limited, especially in small diameter sizes below 100 mm.

Therefore, they propose a robot which uses two wheeled chains instead of the common three. The angle between these chains are 180 degrees so it is easily possible to mount different sensors for different working environments on both sides of the in pipe robot. Each chain is controlled by two motors, one for driving and the other one for steering capability. Count wheels make the steering through a screw motion and another set of wheels brings up a linear motion with the ability to overcome singular motion issues at obstacles.

The robot weights 237 g with a length of 80 mm and can handle pipelines with a diameter from 80 to 100 mm, reaches a velocity of 14 cm/sec and his serial communication distance (Com) is set to 15 meters.

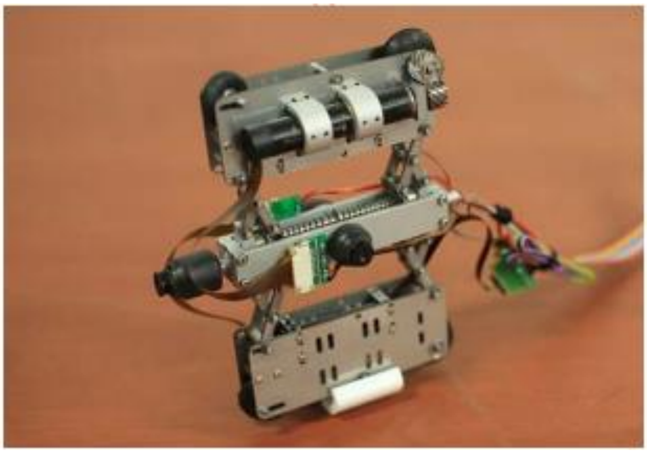


Figure 40: Robot with two wheel chain mechanism by (Kwon et al., 2011)

(Kakogawa and Ma, 2010) focused their research to gain a good locomotion on the aspects fast mobility, good performance with minimum control issues, light weight, energy efficiency and the capability to move in vertical pipes. In their paper they described a hybrid in-pipe robot which combines wheel, wall-pressing and screw type locomotion.

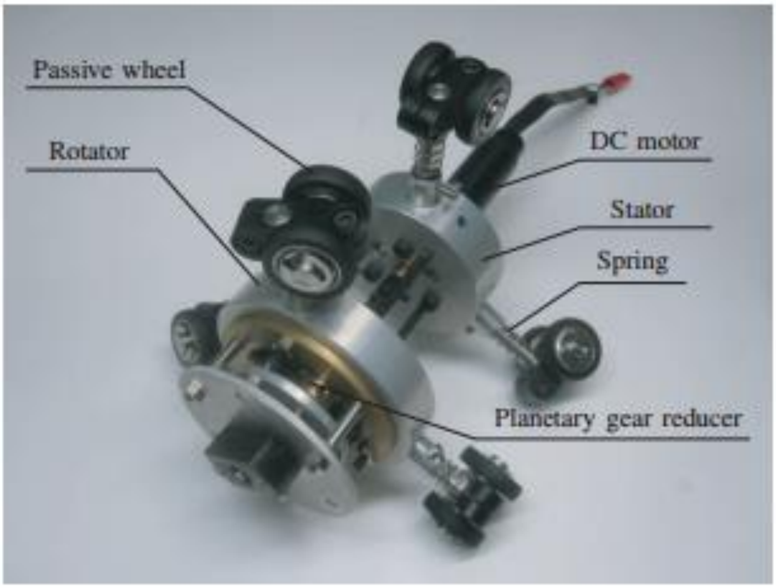


Figure 41: Prototype of wheel type by (Kakogawa and Ma, 2010)

The developers chose wheels because of the strong velocity ability compared to a walking or snake type, wall-pressing because of the demand to move in vertical pipelines as well to have a good adhesion coefficient between the used wheels and the pipe wall and screw type to move forward inside the pipeline.

The developed prototype is able to operate in small pipe diameters, because the robot itself has a diameter of 0,9 mm and is 156 mm long and is shown in Fig. 41.

Also (Se-gon Roh et al., 2008) argued in their paper that mobility inside the pipeline is a crucial factor for designing locomotion systems. The combination of a wheeled type locomotion with a wall-pressing one, as shown in the work from (Kakogawa and Ma, 2010) above, are promising special mobility capabilities. In further literature often the problem occurs that the robots are good at movement in horizontal or curved pipelines but have poor steering properties in case of branches. Out of this the developed they constructed an in pipe robot for 8 inch pipelines called MRINSPECT V, which is not only able to overcome branches, it also can change its driving power regarding to the present conditions inside the pipeline. MRINSPECT V is also able to reduce the thrust force through a stretch mechanism to the wheels when a change in pipe diameter occurs. The robot consists out of three driving units, where every unit uses a magnetic clutch control to be either in active or in idle state. Running all driving units at the same time is very intense in terms of energy consumption, but there are use cases for other robots, for example in horizontal pipes, where all units have to be active. This can cause problems in the number of wheel rotations of the different driving units when there is a change in pipe diameter and in the end result in slipping down the pipe wall. (Se-gon Roh et al., 2008) are overcoming this problem by implementing a clutch based selective driving algorithm, which makes it possible to run only one driving unit instead of all three together. This can save power as well as preventing the robot to slip down the pipe wall.

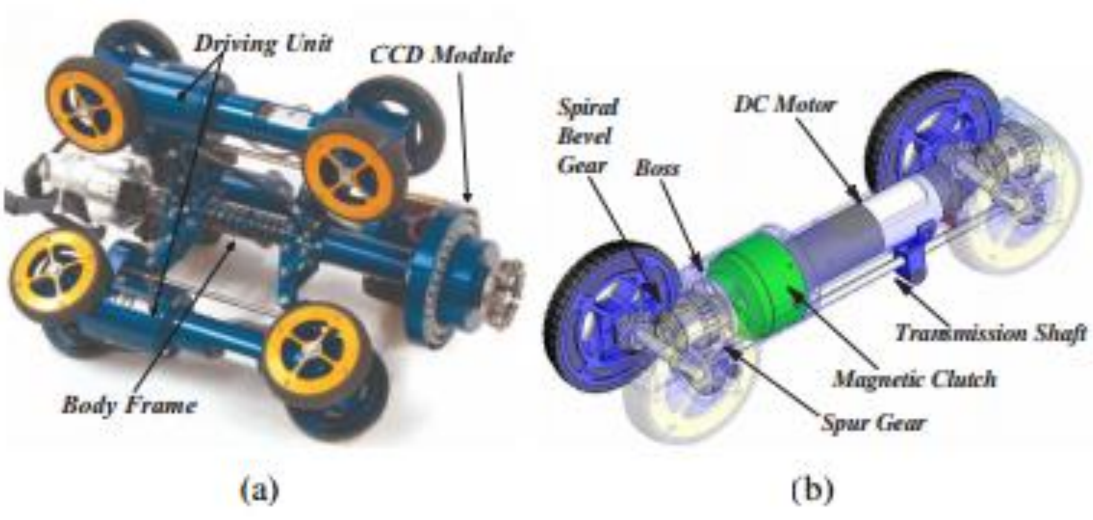


Figure 42: Driving Module a)Whole robot; b)Driving Unit (Se-gon Roh et al., 2008)

Another approach for in pipe inspection was done by (Feng et al., 2009), because they introduced a crawling robot which uses wheels instead of creeping or step walking to increase speed and efficiency. The robot has a length of 4.3 meters, can supply a traction force F_t of 1500 lbs and is shown in the Fig. 42.

Figure 43: Tractor downhole crawling robot (Feng et al., 2009)

Pipeline robots have almost the same functionality as downhole robots which inspect the wells. Tractor downhole robot can be a good example to that, which is shown in Fig. 43.

A detailed explanation of the variables mentioned several times in the literature is given in the next chapter.

3. Variable classification and definition

As indicated in the state of the art, there are lots of researches, developments and applications of pipeline inspection robots. It is important for a development to know and analyze the variables in order to state the borderlines of development, to formulate the requirements and have a better planning and evaluation of the developing robot. On the other hand, variables are important part of the planning and supporting phases since in locomotion the parameters are determining the dynamic behaviors of robots. In this research, the parameters are defined as variables of locomotion and classified first time in this field and evaluated as in following sections. Detailed explanation and definitions of variables individually are given in subchapters 3.1.3 and 3.1.4.

3.1 Variables of locomotion

Out of literature reviews and other relevant information collection activities following general and specific variable set has been used. Those variables and definitions are explained in following subchapters. However, as a novel approach, two types of classification of the robotic variables are carried out.

3.1.1 I Classification of variables

First type of classification is made due to commonly usage of the variables as main and specific ones. Main variables are most commonly mentioned and in some cases evaluated variables. However, specific variables vary due to the intention of usage of robot and other settings. In other words, main variables represent the basic requirements or environmental specifications which take place during the development of a robot. However, the specific variables define specifically the parameters which also occur during the development.

Main variables

1. **V** = Robot´s velocity
2. **P** = pressure in pipeline
3. $\mathbf{I_g}$ **=** weight use factor
4. **Ø** = slope angle of the pipeline to ground
5. $\mathbf{O_b}$ **=** obstacles
    - **ho =** height of obstacles

- **wo =** weight of obstacles

6. **R =** radius of the pipeline

7. ∑**F** = sum of all forces

- **F_t =** tractive force
- **F_d =** thrust force
- **F_f =** friction force
- ∑**N** = sum of all supporting forces regarding to gravity
  - N_1 = gravity force

8. **T =** output torque of the adjusting motor, N.m

9. **PS =** Power supply

10. **m =** Payload

Specific variables

1. **M** = movement directions
2. **Φ_f =** velocity of the flow of the fluid inside the pipeline
3. **C** = temperature inside the pipeline
4. **K =** additional material specifications of the pipeline
5. **μ =** adhesion coefficient between driving wheels and pipe wall
6. **R_R =** robot's radius (can be diagonal in different shapes)
7. **F_l =** flexibility of connection / DOF
8. **S_t =** stiffness of connection
9. **Θ =** Wheel angle of the pipe base
10. **L** = length of the pipeline
11. **ρ_f** = density of the fluid inside the pipeline
12. **α** = curve angle (r_x = curve radius)
13. **$\#_B$ =** number of bodies / universal joints
14. **S =** safety or accessibility of a robot
15. **B =** degrees of freedom or turning angle of joints / wheels
16. **Com =** Communication port of the robot

On the other hand, the second classification method can be used for the variable classification of in-pipe inspection robots.

3.1.2 II Classification of variables

Second type classification is determined more precisely due to pre-defined constraints such as working environment, robotic behaviors and interaction. Since the variables of in-pipe inspection are either environmental variables, or robotic variables, or the variables those occur in the interaction of robots with its surrounded environment, or there can also be some specific variables which is not in any of those subgroups.

Working Environment Variables

1. **P** = pressure in pipeline
2. **Ø** = slope angle of the pipeline to ground
3. **C** = temperature inside the pipeline
4. **K =** additional material specifications of the pipeline
5. $\mathbf{O_b}$ **=** obstacles
   - **ho =** height of obstacles
   - **wo =** weight of obstacles
6. **R =** radius of the pipeline
7. $\sum$**F** = sum of all forces
   - $\mathbf{F_d}$ **=** thrust force
   - $\mathbf{F_f}$ **=** friction force
   - $\sum$**N** = sum of all supporting forces regarding to gravity
     - N_1 = gravity force
8. **L =** length of the pipeline
9. $\mathbf{\Phi_f}$ **=** velocity of the flow of the fluid inside the pipeline
10. $\boldsymbol{\rho_f}$ = density of the fluid inside the pipeline
11. $\boldsymbol{\alpha}$ = curve angle (r_x = curve radius)

Robotic Variables

1. **V** = Robot´s velocity
2. $\mathbf{I_g}$ **=** weight use factor
3. **M** = movement directions
4. *$\mathbf{F_t}$* ***=*** *tractive force*
5. **T =** output torque of the adjusting motor, N.m
6. **PS =** Power supply
7. **B =** degrees of freedom or turning angle of joints / wheels

Interaction Variables

1. **μ =** adhesion coefficient between driving wheels and pipe wall
2. **Θ =** Wheel angle of the pipe base
3. $\mathbf{F_f}$ **=** friction force

Specific Variables

1. **Δm** = mass of the fluid
2. $\mathbf{F_l}$ **=** flexibility of connection / DOF
3. $\mathbf{S_t}$ **=** stiffness of connection
4. $\mathbf{\#_B}$ **=** number of bodies / universal joints
5. **S =** safety or accessibility of a robot
6. **Com =** Communication port of the robot

Both classification methods are applicable and can be chosen by researchers or developers accordingly to their needs. However, first type if classification is more useful for firms and stakeholders of the industry; meanwhile, the second type is better in precision and useful for developers. This approach also defines the weight factors which will be discussed in last Chapter.

Such classification of variables in industry is rare to find, however is useful and essential in defining the evaluation parameters of the projects. Usage of variables, definitions and their classification methods will be well explained later in this chapter.

3.1.3 Variable classification and main variables

As mentioned in previous subchapters, variables can be classified in two ways. Either two column-classification method should be followed which enables the developers to identify the main variables and the specific parameters as well as the four-column classification method. In the second method, we can classify the variables in four sub-topics. Working Environment Variables - which are the variables those define the specification of inspected pipeline and geometrical specifications as well as the material conditions and other environmental constraints affecting the inspection robot. The Robotic Variables which are the variables those define the intended or achieved physical capabilities and activities of the inspection robot. The Interaction Variables which are the variables those specify the interaction conditions of the robot with environment and the other variables specified as specific variables.

Due to the first classification method and as outcome of the literature review, following variables and their mentioning points are indicated. The calculation is due to the given variables and the given importance to variables in the literature. The whole calculation list and the index are shown in the Appendix A.

Main variables:

1. **V** = Robot´s velocity – mentioned, 53 points
2. **P** = pressure in pipeline – mentioned, 45 points
3. $\mathbf{I_g}$ **=** weight use factor – mentioned, 44 points
4. **Ø** = slope angle of the pipeline to ground – mentioned, 49 points
5. $\mathbf{O_b}$ **=** obstacles – mentioned, 31 points
    a. **ho =** height of obstacles
    b. **wo =** weight of obstacles
6. **R =** radius of the pipeline – mentioned, 69 points
7. ∑**F** = sum of all forces – mentioned, 62 points
    a. $\mathbf{F_t}$ **=** tractive force
    b. $\mathbf{F_d}$ **=** thrust force
    c. $\mathbf{F_f}$ **=** friction force
    d. ∑**N** = sum of all supporting forces regarding to gravity
        i. N_1 = gravity force
8. **T =** output torque of the adjusting motor, N.m – mentioned, 60 points
9. **PS =** Power supply – mentioned, 59 points
10. **m =** Payload – mentioned, 43 points
11. **M** = movement directions – only mentioned, 14 points
12. $\mathbf{\Phi_f}$ **=** velocity of the flow of the fluid inside the pipeline – mentioned 20 points

13. **C** = temperature inside the pipeline – slightly mentioned, 6 points

14. **K =** additional material specifications of the pipeline – mentioned, 20 points

15. **μ =** adhesion coefficient between driving wheels and pipe wall – mentioned, 30 points

16. $\mathbf{R_R}$ **=** robot's radius (can be diagonal in different shapes) – mentioned, 47 points

17. $\mathbf{F_l}$ **=** flexibility of connection / DOF – mentioned, 20 points

18. $\mathbf{S_t}$ **=** stiffness of connection – mentioned slightly ,11 points

19. **Θ =** Wheel angle of the pipe base – mentioned, 19 points

20. **L =** length of the pipeline – mentioned, 37 points

21. $\boldsymbol{\rho_f}$ = density of the fluid inside the pipeline – mentioned, 14 points

22. **α** = curve angle (r_x = curve radius) – mentioned, 24 points

23. $\mathbf{\#_B}$ **=** number of bodies / universal joints – mentioned, 29 points

24. **S =** safety or accessibility of a robot – less mentioned, 13 points

25. **B =** degrees of freedom or turning angle of joints / wheels – mentioned, 23 points

26. **Com =** Communication port of the robot – mentioned 50 points

As clearly seen, some of the variables are not mentioned properly, or only mentioned but not taken into account in the robotic development due to the literature review. On the other hand, there are several parameters which is not taken as variables into account. Those variables are shown as own variables below:

Own parameters:

S= safety and accessibility of pipeline

ρ_f= density of the material inside the pipeline / Flow rate

C= temperature inside the pipeline

M= movement directions

This is the first work where almost all variables of the in-pipe inspection are evaluated, analyzed and assessed. So far there was no such work which contains all possible variables, explains and takes into account while designing the in-pipe inspection robots. The details of mentioning point's evaluation out of literature review is not detailed covered in this section due to borderlines of this work, however the table of the outcomes can be found in Appendix A.

In the next subchapters each of the variables are well explained and defined:

a. V = robot´s velocity

The velocity of the robot variable is the in-pipe distance that is travelled by the robot in a given time. More clearly, this is a measure of the robot's movement speed inside the pipeline. Since the pipeline geometry is cylindrical, there are significant velocity calculation difference rather than the plane systems. This difference is highly sensed especially in projects with helical motion planned. In such cases, velocity of the robot is calculated by the axial velocity of the rotator side of the robot:

$$V = \omega \cdot R \cdot \tan \alpha$$

Where R is the radius of the pipeline, ω is the rotation velocity, and α is the tilting angle of the wheels of the robot. (Horodinca et al., 2002)

Otherwise, the Velocity is the rate of change of robot's position due to the reference point in a given time. This variable is a function of time.

b. P = pressure in pipeline

The PIGs movement and whole usage is totally dependent on the sufficient amount of the achieved pressure to "push" the pig through the pipeline that it moves. The pressure level inside the pipeline must be enough to accommodate the additional pressure drop across the pig along with the expected pressure drop needed to maintain the flow capacity and its associated pipe friction loss. (Vradis, 2004)

For the inspection robots of un-piggable pipelines pressure is also an important variable since it directly affects the efficiency of locomotion of the robot as well as the activities of the mechanism. Therefore, it should carefully be considered during the development. Pressure in pipelines can be easily sensed by pressure sensors and can be calculated if the flow rate and other relevant specifications are known.

c. Ø = slope angle of the pipeline to ground

Slope angle of the pipeline to the ground is a variable that affects the pressure, gravity and other kind of force distributions. All long distance pipelines have either a common slope or partial slopes to the ground. This means, pipelines partially change positions and creates angles to the horizontal line of the ground when it goes further. Therefore, it affects the flow force, pressure as well as other variables when it changes the angle.

This variable should be considered as minimum and maximum angles it creates during its length – L. In spot calculations or calculations of forces of the robot in one position, the actual angle should be taken into account. If calculation covers a range, then minimum and maximum angles should be calculated. If maximum slope angle is still in the capability range of the robot, then average angle is taken into account in calculations.

d. O_b = obstacles

The obstacles are the geometrical changes, accumulations or other type of physical occurrences which affects the locomotion, limits or stops in-pipe inspection robots while it moves. There are several applications and algorithms of robotic locomotion on obstacle avoidance. However, in-pipe inspection robot developments change locomotion type or use some design tricks (such as caterpillars, narrow wheels, high accurate legs and so on.) to avoid the obstacles. Obstacles are essential limitation of inspection inside the pipeline. Whereas, some applications are successful in obstacle avoidance, but others limit their locomotion due to the obstacles.

Here, it is significant to study the obstacles deeper. There can be some obstacles which should be ignored when they are in ability range of the robot. Or some obstacles can be removed or moved by the robot along.

α. h_o = height of obstacles

Height of the obstacles defines the highest distance from pipeline wall to the obstacle end. Here, h_o can be taken as different constraints in different obstacle types such as: the percentage of the pipeline diameter occupied by obstacle, the area or the volume of the obstacle and the physical height of the obstacle.

β. w_o = weight of obstacles

Weight of the obstacle plays a major role in deciding if the obstacle is removable or if it can move along with the pipeline. Because removing or moving is the first and best solution of obstacle avoidance. Of course in in-pipe inspection task it is hard to calculate the exact weight of the obstacle; nevertheless it is possible to calculate roughly due to its size, volume and material density.

e. R = radius of the pipeline

Radius is one of the decisive main variables in in-pipe robot development. In most cases main decisions are taken due to the radius of the pipeline in which robots tends to perform.

In middle size pipelines a pantograph mechanism or elastic and/metal string DCAM is used in Robot's drive mechanism to be actively adaptable to diameters or radius changes. A pantograph mechanism is able to adapt the robot's performing diameter up to 500 mm change in diameter in medium size pipelines, whereas other elastic DCAMs are not capable of adapting that much to the radius change. (Park et al., 2009)

As seen in the pantograph mechanism example, the adaptive mechanisms are designed to be able to adapt the internal radius of the pipeline.

The radius of the pipeline is indicated as the diameter or half diameter - the radius in different development projects.

f. $\sum F$ = sum of all forces

This is a very hard variable to adapt from one to another and to classify in groups and make normalizations. However, different nomenclatures are observed in different applications. Sum of normal force is not that complicated in the pipeline robots with simpler drive mechanisms.

But if there is combined or hybrid locomotion, those forces should be carefully classified and measured.

Forces are not only measured with the sensors, could be also measured by the analysis of positions of joints and strings especially in DCAMs. (Park et al., 2009)

Some of those affecting forces are defined below.

α.* F_t *= tractive force

A pipeline inspection robot should reach a sufficient amount of tractive force to pull its tether cable as well as other required parts if applicable, to be able to complete the actions and perform the inspection, maintenance or repair tasks.

If all pressures applied to wheels or other traction mechanisms by the weight, payload and pulling forces of cable denoted by $\sum N$ and the sum of the pressures of the wheels to the pipelines' wall denoted as $\sum P$ then the tractive force can be calculated as following:

$$F_t = (\sum N + \sum P)\mu$$

In which µ represents the adhesion coefficient. (Zhang and Yan, 2007)

β.* F_d *= thrust force

The thrust force is meant to represent all possible reaction forces to the robot. There are many thrust force causing affects such as actuator's torque should produce a thrust force, which can drive translation of parallel linkage to change the radial considering the tractive force equation above for the specific example considered. For other applications, to consider thrust force as one of the main variables, Resistive Force Theory should be applied.

χ.* F_f *= friction force

Friction force stands for calculation and assessment of the force between the pipeline walls and robot's touching part like wheels, caterpillars or legs. This can be formulated with respect to tractive and thrust force. Most of the robots with self-adjusting mechanisms have friction sensors. Friction Force is correlated to adhesion coefficient and slippage rate of the material inside the pipeline.

Friction force is one of the main elements to be considered since it is the main power consuming due to the loss force and power, and it mainly defines the efficiency of the locomotion type of the robots.

δ. ∑N = sum of all supporting forces regarding to gravity

Gravity is one of the main supportive forces applied to moving vehicle. Inside pipelines it is essential to take the gravity into calculation of forces with respect to the slope of the pipeline to the ground. Gravity force applied is multiplication of mass or weight of the whole system and the gravity factor unquestionably whole calculation should be normalized by taking the slope angle of the pipeline to the gravity direction.

All pipeline inspection robots should take gravity force under consideration, since it is one of the decisive factors for designing the locomotion.

g. T = output torque of motors, N.m

There are several ways to determine the torque especially while planning and calculating the robot's locomotion inside the pipeline. One of the non-sophisticated ways to accept and calculate the torque is by considering vertical movement of the robot inside the pipeline. Thus, enables developer to be able to consider the applied forces distributed equally as well as to not to deal with the slope factor of the pipeline and other issues.

When the robot is moving vertically and if the n numbers of tractive parts (wheels, caterpillars etc.) are touching to pipeline wall and if the traction forces exerted on the torqueing mechanisms are the same, each reaction force F_{cx} at the body is $\frac{1}{n}$ of the total weight of the robot structure. It is the same as traction force as mentioned above. Thus, the minimum torque capability of the actuators enclosed in the touching mechanism is calculated by:

$$\tau = F_{cx} r = \frac{Wr}{n}$$

Where r is the radius of wheels and W represents the total weight of the robot. W or derived to I_g will be explained in next section. (Chen et al., 2004)

h. ***I_g = weight use factor***

Due to the equations of variables and constraints above, the position of weight use factor can be clarified as the amount of the weight of robot which contributes to the tractive capacity. If *mg* denotes the total weight of the robot and $\sum N$ denotes the sum of the all supporting forces, we obtain following equation for the weight use factor (Zhang and Yan, 2007):

$$I_g = \frac{\sum N}{mg}$$

i. ***PS = power supply***

Power supply represents the electric power consumed by the mechanism and supplied from the power source. The electric power of robots usually being consumed by sensors and actuators as well as the DC motors. Those motors' power consumption is related to the current they spend, which has direct ratio with the second power of the current. And the current has the direct ratio with the torque. Therefore, the torques of driving mechanism defines the amount of electric power consumption.

$$P_d = \sum_{i=1}^{n} \tau_i \, \omega_i$$

In the equation n is the number of driving mechanism (wheels) and ω stands for angular speed of driving wheels. Thus, from the equation we can obtain the total power needed by adding loss power P_w caused by slipping and the slope of the pipeline and calculated as,

$$P_w = (1 - \delta)P_d$$

In which δ is the slipping rate. If the control unit's demanded power and required power of sensors added, required power to be supplied can be calculated. (Chen et al., 2004)

j. ***m = payload***

Payload of the robot is mainly meant the maximum amount of allowed axial force with the own weight of the robot while the robot tends to move towards upward in vertical position. (Horodinca et al., 2002).

3.1.4 Specific variables

Specific variables are well defined in following subchapters.

a. M = movement directions

This variable is also essential in motion planning and whole projection of robotic development. M indicates simply vector directions of the robot in which the robot is either intended or could move. Movement directions can be applied by taking a starting direction or zero point by having coordination under consideration. These directions can be formulated in one or more of the coordination standards. However, possible movement directions are indicated in Chapter 4 in Cartesian plane calculation environment.

b. Φ_f = velocity of the flow of the fluid inside the pipeline

The velocity of the flow inside the pipelines is primary for its affection in forces and movement directions as well as the pressure of the material to the robot. Velocity of the flow is important when the robot is intended to be used in-use case. The velocity is also a vector dimension and should be inserted to calculation with the right directions to the normal vector direction accepted.

c. C = temperature inside the pipeline

Temperature inside the pipeline affects the movement, adhesion coefficient, pressure and other relevant constraints of the robot. Therefore, it should be taken into account carefully. There are some temperature ranges in which robot can perform and in which robot’s normal behaviors can show changes. Sensors of the robots are very sensitive to the working temperature in the pipelines or the temperature changes.

Temperature inside the pipeline can be measured by the sensors or thermometers and also calculated by the outside temperature, material specifications and other environmental effects taken into consideration.

d. K = additional material specifications of the pipeline

Oil pipelines are built with carbon steel pipes, with diameter ranging from 200 mm to 500 mm. the length of those pipelines can be extended to hundreds of kilometers. (Okamoto et al., 1999)

Those pipelines can have different specifications which would affect the pressure, temperature transmission differently. On the other hand, material specifications define the slipping rate and adhesion coefficient directly. It can be defined and assumed independently and is changing by different materials and densities depending on the pipeline material.

e. μ = adhesion coefficient and slipping rate

μ represents the sum of effective constants that decides the slippage and defines the friction force as well as the loss power. It has three main dependents such as adhesion coefficient, slipping rate and the coefficient of increasing force or rolling denoted as φ, δ and $k(\text{or } f)$ respectively. The ratios are

$$\delta = k\varphi$$

And

$$\mu = \binom{\delta}{\varphi}$$

(Chen et al., 2004)

The correlation and derivative of the equation above is not in the focus of this work, therefore it is not explained in details. However, it is important to understand the ratios of adhesion coefficient, slipping rate and other coefficients of increasing forces or size constants to take precisely into account while developing an inspection robot for the pipelines. Those coefficients depend on the material specifications and other environmental constraints of the pipeline.

f. R_R = robot's radius

R_R is the basic and final variable of the in-pipe inspection robots. This variable supposed to be defined after taking all requirements, environmental constraints and limitations into account.

This variable is thought as the longest half dimension of the robot. In a cylindrical or spherical design, it should be defied as the radius of the robot. In other cases, half of the diagonal will be considered as the radius, if the robot is designed in other shapes than mentioned ones.

Theoretically, the radius or the diagonal of the pipeline inspection robot should be less than the inner radius of the pipeline, if the pipeline is smooth and without any accumulations or obstacles. This can be formulated as:

$$R_R \leq R_P$$

In other cases, evaluation of maximum allowed radius of the robot should include depending variables as well. In inspection of the pipeline with obstacles, the definition should include a respective calculation which includes height and other measures of the obstacles inside the pipeline, which is explained in obstacles section.

g. F_l = flexibility of connection

Most of the pipeline inspection robots are being built with a modular design which allows having more degrees of freedom and flexibility in motion inside the pipelines with slope, curves and branches. In such cases flexibility of connections (in some cases universal joints) plays a major role to identify motion limitations of the robot and its path allowances. Flexibility of such connections and joints defines degrees of freedom of the joints and the robot solely.

In some applications mentioned flexibility has been achieved by rubber connections, universal joints, strings and flexible materials. This is significant information and requirement to be able to design and plan a better performing robot with much coverage of inspection.

h. S_t = stiffness of connection

In connections, joints and intersections of the parts of the robot more flexibility is being achieved as mentioned above. However, more modular is the robot, more rigidity has the connections. This rigidity increases the accuracy of movement and decreases the precise path following. Stiffness is the measure of rigidity of the connection. This is defined as:

$$S_t = \frac{F}{x}$$

In the equation above F stands for the force and x is the deformation and displacement of the material. Stiffness is the resistance of elastic body to deformation.

i. Θ = wheel angle of the pipe base

This variable denotes the slope angle of the drive mechanisms part which touches the wall of the pipeline. If a robot is moving with wheels, then this is an important constraint which symbolizes the wheels' touching angle to the pipeline walls' normalization vector. Wheel angle of the pipeline base is important to calculate the weight factor or force distribution.

If the robot is moving with legs, then it denotes the tactile angle of the robots' feet to the ground. There are some applications which take force sensing into account by tactile sensors at the bottom of the legs like MORITZ. (Zagler and Pfeiffer, 2003)

j. L = length of the pipeline

Length of the pipeline is another important factor of the pipeline. Length of the pipeline is decisive in most cases for decision making in pipeline inspection. Due to the pipeline technology conference IPC 2016, there are 2.5 million kilometers high pressure pipelines worldwide where 25 thousand kilometers are being built annually in addition. This shows the importance of the constraint – the length of the pipelines.

Length of the pipeline should be considered as the segments' length which requires inspection. Since the pipeline inspection robot's movement is limited due to several issues like inspection-possible segments of pipelines, battery life of the robot, tethered cable length, movement limitations, ability to communicate and data storage and communication capability, length of the pipeline is important to know and define such limitations.

k. ρ_f = density of the fluid inside the pipeline

Although it is one of the least mentioned and considered parameter in robot development, density of the material is essential in defining the motion and processes settings of the robot. Density of the flowing material is important to calculate the forces which will be applied, gravity affect and other density of the flowing material does not only decide the locomotion, at the same time decides the material specifications and material definitions of the developing robot. For example, the joints of water pipeline inspection robots are built by the plastic material filled with air, only because it will have a slight difference of densities with water and the plastic will be a bit denser.

l. *α = curve angle (r_x = curve radius)*

Pipelines in usage have significant curves, branches and other geometrical instabilities due to intention of usage, distribution and environmental effects. Curved pipelines are common ones among them. Pipeline curves are nowadays designed to not to cut off the flow or slow the flow velocity down. However, the huge parts of the pipelines need inspection have the curves. One of the main reasons of pipelines being un-piggable is the curve angles and other geometrical shape changes of pipelines. Thus, the problem underlies when the bends are curves are applied unregularly, or the curve angles are really small. For instance, bends/elbows (90-deg) with bend radius less than 1.5xDiameter is by far the most common obstruction for defining an un-piggable pipeline or while deciding if the pipeline geometry allows pigging and pigged inspection or not before testing. (Vradis, 2004)

Therefore, curve angle plays a major role in inspection planning and robot development for in-pipe activities. Curve angle is accepted as an important parameter for path planning of the robot, and measure either with degrees or with the ratio of the diameter.

m. *$\#_B$ = number of bodies / universal joints*

To achieve better steering capability and maneuverability, as well as locomotion in Y, L or T branches it is essential to design pipeline robots with more than one body, in order to be able to move through elbows and other geometrical shape changes of the pipeline. On the other hand, number of bodies is an important parameter on development. Most of the developed robots have more than one body, connected with either a universal joint or with other kind of connectors. (Hirose et al., 1999) developed a new concept called “Whole-Stem Drive” which intends to have more than one body, connected with a “stem” in which drive mechanism leads this “stem”. On the other hand, for the clamp-drive type pneumatic robots such as (Lim et al., 2008) developed is having three parts, three bodies but directly connected.

n. S = safety or accessibility of a robot

Safety is not involved in pipeline robots as other applications of robots, since the term Robot Safety stands mostly for the human safety in robot- human interaction. Since the operator of the in-pipe inspection robot usually stand far away from the device, such kind of accidents can occur in installing or de-installing robot to the pipeline. Otherwise, it is hard to talk about accidents of pneumatically driven robot accidents in pipeline which affects the human operator.

An explosion can occur while using the electric drive robots inside the pipelines while pipeline has flammable material inside, but if the pipeline is inspected in in-use case, the explosion would be hard. If you have an electric drive mechanism, you have to have a special mechanical construction and cover around the motors or connections to prevent the explosions.

In this dissertation, robot safety and accessibility stands as a unified parameter of the robot's safety for themselves and of course accessibility in order to prevent any accidents or stucks which can harm the robot or to rescue the robot for the safety or further functionality.

o. DOF = degrees of freedom or turning angle of joints / wheels

Degrees of freedom (DOF) also define the maneuverability of the robot inside the pipeline more precisely. Theoretically more degrees of freedom give more flexibility to the robotic joints, thus cover more range of pipelines and geometrical shape changes of pipelines to be inspected by the robot.

This variable defines the maneuverability as mentioned in the variable called flexibility, moreover defines the flexibility and covered inspection range of the sensors – or any other jointed part of the robot. Flexibility defines the motion flexibility of the robot, whereas DOF stands for other joint flexibilities than inter-modular connections, such as cameras, laser measurers and etc. as mentioned above, more degrees of freedom means more areas to be inspected and better precise measurements and sensing.

p. Com = communication port of the robot

Communication port of the robot is a variable which defines the limitations or the specifications of the communication type of the robot that supplies the communication between operator and the robot.

Most of the in-pipe inspection robots which are available commercially or for inspection are tethered devices. Therefore, communication between control room and robot as well as the energy supply is transferred by the tether cable. However, some researches go on to create un-tethered in-pipe robot. The energy issue is solvable by the use of batteries; however, the communications problem is not easy to solve. (Mirats Tur and Garthwaite, 2010)

Tethered solutions are good enough unless the stiffness problem, length limitation and tractive force decreasing occur.

Communication for untethered robots is partially solved for some cases such as for the pipelines unburied and for those emptied before inspection. The case for buried pipelines is not solved yet. Therefore, communication type of the robot is essential for the design (Mirats Tur and Garthwaite, 2010)

3.2 Assessment of variables and Evaluation Criteria Formation

Due to the variable definitions above and the consideration of the variables in different development projects, it can be summarized that not all the aspects of the affecting constraints are covered in all projects and taken into account as explained in previous subchapters. Therefore, so-called own parameters are created and defined in Chapter 3.1.3.

However, for a reliable development as well as for robust evaluation it is crucial to take all dependent variables into account. Hence, the evaluation criterions are formed due to the needs of different stakeholders of different phases of inspection; those criterions are well defined by the variables.

For example, working environment is an essential criterion for evaluating the inspection robots and this criterion can be precisely defined if all relevant variables like the radius, velocity, adhesion coefficient and others are taken into account. Autonomy of the robot would be another crucial assessment criterion and it highly depends on the length of the inspected pipeline, communication and control mechanism and so on.

Therefore, assessment criteria are directly correlated with variables and are dependent within each other.

In the following table the criteria of assessment of robots and affecting variables are shown:

Criteria of Assessment	Affecting Variables
- **Working environment specifications**	R, V, m, C, K, µ
- **Commercial Availability**	S,PS, Com
- **Autonomy of the robot**	L, #B, S, Com,
- **Energy supply**	PS, T, I_g, Com
- **Control mechanism**	L, Com, T
- **Production Costs**	PS, K, R_R, #B
- **Hydrodynamics**	V, P, I_g, ∑F, Φ_f, R_R, ρ_f
- **Locomotion efficiency**	P, Ø, Ob, ∑F, Φ_f, µ, DOF, α, r_x
- **Maneuverability**	Ø, T, M, R_R, DOF, α, B; r_x
- **Detection technology**	Ob, L, R, K

Table 3: Criteria of assessment and affecting variables

Table 3 is derived from criteria with highly dependent variables in direct correlation and proportion. Of course, this table can be developed further but within the scope of the dissertation only highly directly proportional constraints have been taken into account and recognized as primary correlation. If secondary and tertiary correlations would be considered table could be expanded and the number of criteria would be increased. Due to the delimitations of this work, only essential criteria formatted and major dependencies considered.

Assessment criteria will be discussed and defined detailed in the next chapter.

4. Assessment of in-pipe inspection robots

There are several applications and researches on grading the robots in industry, as well as in-pipe inspection mechanisms. Almost every development project assesses previous developments of robots which are designed for same requirements and tasks inside the pipeline. As classification of the pipeline robots, evaluation and comparison is usually on locomotion method. For example, (Kakogawa and Ma, 2010) claim that screw drive mechanism is better drive type to travel inside the pipeline due to the number of actuators needed for smaller radius pipelines. Such drive mechanism can also be built by only one actuator. They also explain why walking mechanisms are worse than others due to needed actuators number and energy consumption (Kakogawa and Ma, 2010). However, none of the assessments or comparison are based on a complete method or criteria. Therefore, there is a need in this field to create precise determination of the robotic development. Therefore, 5-points evaluation method is derived and developed.

4.1 5-points evaluation method

In order to create the optimal evaluation of pipeline robots, the formation of evaluation criterions is essential. Considering all main variables and specific variables mentioned above, ten comparison criteria have risen. The principle of defining various categories and evaluating the devices according to these categories, such that a single, comparable value can be calculated for each device, is based on the work of Haas (Haas, 2012), where such a model has been presented for the evaluation of EoL values of automation devices.

In this evaluation method each evaluated project is graded from 5-points due to each of 10 criteria. In total grading sum will be from 50 maximum points evaluated.

4.1.1 Assessment criterions

From the technology point of view, in-pipe inspection robots' development should solve the issues as efficiency in robot transmission systems, lighter and better tractive locomotion mechanism, reliable, robust and effective control system, high capacity of power supply and efficient supply ways, real time localization, communication, safety and accessibility of the robot and so on. (Chen et al., 2004)

From indicated requirements and defined variables following criterions developed for the evaluation method:

- Working environment specifications
- Commercial Availability
- Autonomy of the robot
- Energy supply
- Control mechanism
- Production Costs
- Hydrodynamics
- Locomotion efficiency
- Maneuverability
- Detection technology

The criteria will be defined and discussed in following subtopics.

a. Working Environment Specifications

Working environment specifications is a criterion which combines most of the environmental aspects of the robots in process. Moreover, this criterion can be defined as robot's calculated and adapted diameter of the pipeline, the thickness of the materials and other important environmental aspects created from environmental variables explained in Chapter 3.1 of the robot's working environment.

Pipeline robots are mainly designed and developed for pipeline inspections – which is a hazardous and hard environment for the human inspectors in terms of safety and accessibility. This is one of the main aspects of robotic development in pipeline industry and environmental variables are the main issues which triggered the development of robot's age for pipelines in petroleum production and distribution.

Working environment criterion has its own calculation method with several aspects as:

- Diameter of the pipeline
- Shape changes in pipelines
- Necessity of robot's usage due to existing environmental requirements

On the other hand, this criterion depends on environmental variables discussed in Chapter 3.

Weight factor of the radius of pipeline intended to use the robot the overall radius of the pipelines. It is obvious that smaller the diameter gets, the more pipeline robot is most likely will be used because of the variable accessibility and it takes more percentage of the usage than other pipelines. In other words, smaller pipelines have greater weight factor – they are more used than the bigger ones. That is why the smaller the radius of pipeline goes; the bigger points should be given to the robot for its planned environment due to the discussed evaluation type.

Diameter of the pipeline is in most cases directly proportional of the shape changes. When pipeline has bigger diameter, it is either the beginning vessel of a pipeline system or it carries directly the material from the origin to the target point and will not have much shape changes. But, when pipeline gets smaller in diameter, it means that pipeline is in the ending of intended target and will most likely have Y-shape, T-shape or other kind of geometrical shape changes.

Since the more adaptable robot is better one in all terms, we will consider the geometrical shape changes within the radius change as indirectly proportional. So, when pipeline radius is greater, it will have less turns, crosses and other shape changes as well as valves, so grading should be less. Therefore, the method aims grading only due to pipeline's radius, that will give certain assessment as taking shape changes also into account, which is expected to give the same result as calculating all other environmental specifications. Therefore, minimization of criterion has been made and aspects simplified to the radius.

In modern research and development period, researchers are striving to build and develop in-pipe robots or mechanisms for intended processes inside the pipelines, which are desired to move in narrow and complex pipelines. (Kakogawa and Ma, 2010)

Since the actual evaluation is based on only the diameter of the pipeline which will be covered below, there are some constraints to be discussed as well, like what happens if the pipeline gets smaller and smaller. We will consider robots adaptive to smaller diameters as better ones, but if pipeline gets smaller it affects the design and control mechanism of the robot. As mentioned in (Horodinca et al., 2002) for smaller diameters than 40 mm, the batteries and the radio receiver should be placed apart from the main body of robot. But later on, this critic diameter reduced to 25 mm, therefore taking borderlines of this dissertation, bottom-line will be taken as 25 mm in evaluation. However, lately researchers claim that the critic diameter is under 80-100 mm. (Kwon et al., 2011)

In this research, pipeline diameter is accepted as essential and main variable of environmental specifications. Shape changes and turns are assumed to be more in smaller pipelines than the bigger ones. Since there should be a starting point for the assessment, exceptions are simply ignored in this work.

Therefore, the grading for environmental specifications will be as following:

DIAMETER	<25 mm	25-50 mm	50-150 mm	150-500 mm	500-1500 mm	>1500 mm
POINTS	5	4	3	2	1	0

Table 4: Environmental specifications grading

b. Commercial Availability

Commercial availability is another important aspect of robot development which should be taken into account carefully in evaluation and comparison of the projects. Since most of the developments are only ideas and a topic for research of institutions and in better case there is only one prototype available, it is very essential to have in mind while developing the robot, that this development should be realized in order to gain usability. Moreover, the idea of building a pipeline robot is essential, but due to the innovation restrictions in petroleum industry and lack of information flow from organizations to others, robots and development methods are being re-invented over and over again.

It is essential to at least build the prototype of robots in order to be able to understand and spread over how the robot should and will look and proceed like. Prototypes are precious period of the development in which researcher or developer learns and understands the most. This is the stage that all development goes from simulation phase to experimental phase.

Prototyping is significant for robot researchers, commercial managers and business people in all senses. This is the main period before developer decides to go on production. Unfortunately, there are not many applications which exist with more functioning prototypes or in mass production.

Commercial availability can be in different situations. First of all, the idea will be generated and evaluated which will be considered as the first and main step of prototyping. Secondly, the availability of prototype may be the next and better logical step of the development. Of course on prototype will not always be enough for the developer or the producer. It is all stakeholders' favor for a development to extend the prototyping in further versions. Therefore, the grading should be considered increasing direction when there are more prototypes available.

In the grading, commercially available is intended to represent the projects which the robot is not for sale, but is used for in-pipe inspections by the developer commercially. There are several applications of pipeline inspection robots which goes beyond prototypes and are already in mass production or commercially available. Naturally, this is the best opportunity for a development and should be graded highest among others. The grading will be respectively:

COMMERCIAL AVAILIBILITY	**Idea phase**	**Concept design / first prototype**	**Fully functional prototype available**	**Further prototypes available**	**Commercially available**	**Mass production**
POINTS	0	1	2	3	4	5

Table 5: Commercial Availability grading

c. Autonomy of robot

There is a discussion and idea discrimination regarding tele-operated devices being called robots. Some of the researchers think a robot is directly correlated with its degrees of autonomy. Degrees of autonomy are a main evaluation point that decides many other criterions' existence. For example, control mechanism architecture is directly depending on autonomy of the robot.

In some applications such as (Horodinca et al., 2002) the autonomy of robot is directly related to its battery life. Therefore, the autonomy of prototype of developing robots in this application is agreed as 2 hours. While correct, due to the guidelines of this work it will be omitted to voluntarily considering the duration of battery life of the robot as autonomy, but the degrees of self-determining and self-decision making skills.

As defined in literature, there are three main types of autonomy in robots such as manually operated, semi-autonomous and fully autonomous robots. In manually operated robots, visual feedback from the site by robot's detectors and sensor are being transferred to the operator and operator manually decides and operates the robot using control panel. In manually tele-operated systems, robots do not have autonomy to decide or react solely. All collected data are being collected by the operator or operators and all decisions been taken by them. Such systems need well-trained human operator to perform all steps taken by the robot such as manipulation, motion, path planning and processing. Almost all robots which are commercially available are manually operated which means zero degrees of autonomy.

Semi-autonomous robots are operated by human operators like manually operated ones but in this case the operator takes only final decisions or relevant actions. All other standardized and pre-defined actions are taken by robot's processor or by the computer on site. In this case, collected data from sensors are transmitted to the processor and main steps are being taken by robot's control unit. On the other hand, visual data is shown to the operator and usually operator can react at any time and even can perform during an automatic process. Operator's involvement is decreased in such robots by development of smart-navigation and collision avoidance systems. KANTARO is the prototype of a fully autonomous mobile robot designed for 200-300 mm sewer pipeline inspection. MAKRO is also one of the prototypes of a fully autonomous, untethered, multi-segmented, self-steering articulated robot which has been designed for autonomous navigation in 300-600 mm pipelines at dry weather conditions. (Kim et al., 2010)

Fully automated robots are performing due to pre-defined scenarios and artificial intelligence's decisions. Such systems don't require involvement of human operators especially during the operation and processes. Since the pipeline robots perform in hazardous and sensitive environments, semi-automated robots are being in favor to use. But, if we consider the perfect automation in terms of safety and with respect to the sensitive environment of the products of oil and gas industry, we can accept fully-automatized robots as the best ones and rank them higher.

In other words, manually operated robots do not decide the inspection process. For example, if a robot is performing photo inspection inside the pipeline for inspection, manually operated robots are not able to navigate and find the cracks themselves. Operators should navigate and when necessary shoot a photo. However, Semi-autonomous robots would find the cracks themselves and would ask the operator to confirm the photo shooting. In comparison, fully automatized robots would be able to find the cracks and take photos without any final confirmation from the operator.

DEGREES OF AUTONOMY	Manually operated	Semi-autonomous	Fully automatized
POINTS	1	3	5

Table 6: Grading of Autonomy of robot

d. Energy supply

Energy supply of in-pipe inspection robots is one of the main figures of the development. Form of energy source and energy transport decides many points in design and development of the robot systems. In energy supply there are few points to be clarified. First of all, batteries are not energy sources; they are energy storages or carriers. Therefore, energy supply of the robots should be taken into account in three steps, such as energy source, energy carriage and consumption.

In other words, developer should decide what kind of energy and from which source will be created in order to feed the electronic parts of the robots. Then, carriage type should be decided. In that phase, developer can decide either source and carriage or storage will remain the same or there will be sort of carriage between the source and energy consuming module – in most cases robot module itself. Such carriage mechanisms can be cables, carrying modules or carrier batteries. Lastly, energy consumption should be decided as, in which part of the robot energy will be distributed.

Energy sources can be different for different applications. The four alternatives considered for a robot power source are wind turbines, rechargeable batteries, fuel cells, and radio isotopic thermoelectric generators (RTGs).

At present rechargeable batteries should be considered as the front runners in the application of robot in the natural gas transmission pipelines. They are probably going to be much less expensive and easier to manage than RTGs, and would have wider public acceptance and fewer regulatory constraints, but would require much more frequent replacement. (Malvadkar and Parsons, 2007)

Batteries, like hydrogen, are not a source of energy. They are useful carriers of energy. In grading this element should be considered as well.

Nevertheless, the grading for assessment will consider the efficiency in combination of energy source, carriage and consumption of the robot. So, the grading is as in Table 7.

Here, energy efficiency is considered the combination of energy source effectiveness, energy transport efficiency, energy consumption and other relevant issues.

BATTERY TYPE	High Energy consumption , no efficiency	Stable energy consumption , very less efficiency	Less Energy efficiency	Average Energy efficien.	More Energy efficien.	High Energy efficien.
POINTS	0	1	2	3	4	5

Table 7: Energy supply grading

e. Control Mechanism

Most of the in-pipe inspection robots are connected with tethered cable or umbilical cord between operating platform and in-pipe robots. Those tethered cables include communication cables, power supply network and data transfer cables. On the other hand, those tethering network supplies a safety rope for the robots to be able to be pulled in case of emergency or when necessary as well as it defines the control mechanism communication.

Design of a control mechanism is highly depending on degrees of autonomy in-pipe robot has as explained above. Design of control mechanism has a main challenge due to the literature, which is the navigation control, specifically steering in branches and smaller pipelines. Developments are in direction of more complex but better navigation systems and algorithms which allow faster communication and coordination of different modules for higher mobility.

Ranking of control mechanism is highly depending on degrees of autonomy and battery – energy source type as well as the intended usage of the robot.

Control mechanisms can also be evaluated by the quantity of control systems which is integrated in the control unit. There can be pre-locking operations control, communications, speed adjustment and position control, posture control, safety control and so on. (Chen et al., 2004)

However, the grading should consider all the aspects and regarding the obtained results grading defined as following:

Control Mecha-nism	Zero Auto-mation	Very less Auto-mation	Less Auto-mation	Average Auto-mation	High Auto-mation	Full Auto-mation
POINTS	0	1	2	3	4	5

Table 8: Control mechanism grading

f. Production Costs

There are important indicators of a robotic development to be considered as a success measure. Definitely cost – quality relation is one of the most important success indicators in most areas of the industry. Cost decides of many other relevant variables in modern world's robotic developments. Most of the research and development projects are being limited due to financial constraints.

Therefore, cost ranking of the in-pipe robots will show more to developers than other ranking criterions. Since cost is the most decisive element for users and firms for development as well as for usage, it should be taken into account more carefully.

There are few elements of cost estimation for in-pipe robots such as material used, standardized devices implemented, sophisticated design, own-designed parts, time consumed in production and research and development time implemented and so on. As seen, out of used, the time is the most valuable constraint of robot design. It is easier for commercially available products to apply the cost-quality correlation. But for other applications, it is hard to estimate used time and costs of the materials. Therefore, we will use more standardized decision making tool as following:

- Used materials – devices
- New techniques applied
- Complexity of design
- Time spent
- Control mechanism

We will calculate each factor as a unit and the cost estimation will not be exact, but will be with comparison of each other. To be able to compare, we should indicate each issue with numbers. Each unit above represents a unit number, and those points will be graded with comparison. For example, the most cost effective robot application would have more standardized devices in use, applied known techniques with less complexity of design and less time spent, with more standardized and cheaper commercially available control mechanism. The least cost efficient ones would be with own-designed devices implemented, with newest possible techniques applied in high complex design, with a lot of time spend and own-designed expensive control mechanism.

Each unit will have grading from 0 to 1.0 among each other. Total number will give the grades of cost effectiveness with respect to cost-quality relation.

Cost Efficiency	**5**	**5-4,0**	**4-3,0**	**3-2,0**	**2-1,0**	**1-0,00**
Points	0	1	2	3	4	5

Table 9: Production costs grading

g. Hydrodynamics

From the beginning of research and development period, it is concluded that one of the most omitted variables of design of an in-pipe inspection robot is hydrodynamics of the robot.

It is an essential constraint of in-pipe inspection robots, since most of the developments are directed towards inspection of pipelines during the usage. If we consider that, in most cases such pipelines are being used for liquid or gas carriage, robots inside should have high efficiency of hydro – aerodynamics in order not to block the flow of the material inside the pipeline as well as for the robot to not to get stuck in the pipeline and move efficiently.

Therefore, we created a calculation of the hydrodynamics of the pipeline robot which will allow us to compare the robots due to their in-situ behaviors.

Hydro, aero-dynamics is directly proportional with robot’s blocking the flow, therefore grading would be accordingly:

HYDRODYNAMICS	Fully blocking	Highly blocking	Average blocking	Half blocking	Very less blocking	No blockage
POINTS	0	1	2	3	4	5

Table 10: Hydrodynamics grading

h. Locomotion efficiency

As already mentioned above, these different locomotion approaches have been developed for different cases, working environments and distinctive competencies and not to be applicable for all purposes. For the user it's hard and cost intensive to find the right way to build such a locomotion system for distinctive requisitions which should fulfill predefined requirements.

Obviously, developers decide and design drive mechanism firstly taking environmental aspects of the work which should be performed by developing robot. In there, more than other important constraints, diameter of the pipeline plays a major role in this decision making. For example, for small size diameters projects follow the simple and traditional earthworm principles. For medium size diameters, piping is taken care by classical electromechanical systems approaches, including wheels and tracks. For larger diameters, walking tube crawler is being proposed. (Horodinca et al., 2002)

During time, a lot of different locomotion types have been developed. These different pipeline configurations make it necessary to find new ways to assess all the requirements for the working environment, which is more and more done by combining the established locomotion types as some shown in Fig. 44.

On the other hand, there are different approaches on defining the locomotion types, which creates more aspects to compare locomotion types with. This topic is covered deeply in Chapter 2.2 of the dissertation. Therefore, here only the ranking system and estimation of locomotion efficiency is discussed.

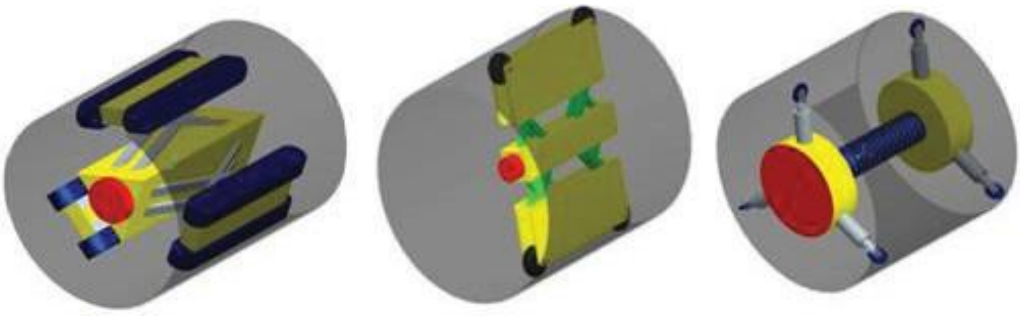


Figure 44: 1) Caterpillar wall- pressed type, 2) Wheeled wall-pressed type, (3 Wheeled wall-pressing screw type (Roslin et al., 2012)

Locomotion efficiency is being calculated by velocity – locomotion type – energy consumed relations with efficiency factor being focused on and is graded as:

LOCOMOTION EFFICIENCY	**No efficiency**	**Poor efficiency**	**Average Efficiency**	**Highly efficient**	**Very good efficiency**	**Excellent efficiency**
POINTS	0	1	2	3	4	5

Table 11: Locomotion efficiency grading

i. Maneuverability

Unquestionably, in-pipe inspection robots' maneuverability is one of the most important aspects of useful robot development. Since pipeline networks usually have curves, connections, separators, blocks, collectors and other geometrical changes of forms, maneuverability rises as one of the most important aspects of robot's intended locomotion and functionality. Therefore, it should be considered as one of the rating aspects of developments.

Usually, pipelines have Y-type, T-type, L-type connections and/or curves, slopes and multi-directional continuing forms. Therefore, in-pipe inspection robots should be developed in a way which covers most of the possible forms where applicable. Developers find different approaches to adapt robots in a flexible way to be able to move in those connections and in different geometrical shapes. Some applications solve this problem by having adaptive design of locomotion systems, others are adapting robots by dividing them in steering parts and have a snake-inspired design while some of the developers omit the importance of direction changing of the robots and design their applications only movable in one direction and in one given specifications of the pipeline.

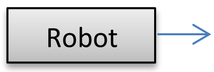
In this ranking point, the evaluation criterion does not only cover the maneuverability of the robots while they move as well as their ability to adapt their locomotion in geometrical form changes of the pipeline as connections and curves.

In some developments, researchers are taking direction changes into account but in a flat surface or in only two-dimensional direction change. In other words, some of in-pipe inspection robots are developed for the pipelines with a specific diameter which goes along a pipeline and will have a turn to right or left, or only up and down. In reality, pipelines have same degrees of direction changes in all dimensions. Therefore, this aspect will also be considered.

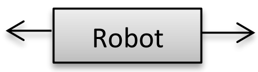
There is another point in maneuverability of in-pipe inspection robots during their locomotion which is rotation problem. Some of the robotic applications, especially ones with crawling and wheeled types move only in one direction where the user defines and in which robot was put in the beginning. In most cases this locomotion is vertical locomotion, which also cuts the flow and has a bad effect on hydrodynamics of the material flow inside the pipeline as explained above. So far, it has not been found any wheeled vertical locomotion robot which can also rotate and become horizontal or vice versa.

The evaluation method defines ranking criterion as following:

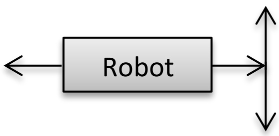
Not maneuverable – primitive movement in one pre-defined direction – solely positive or negative vector direction.



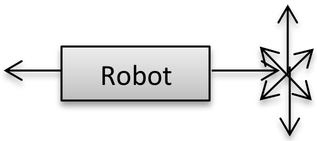
Poorly maneuverable – poor maneuverability is ability to steer only in one radial or one Cartesian direction, both vector directions.



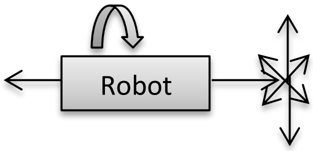
Average maneuverable – able to take two dimensional curved shape changes hardly, no radial rotation



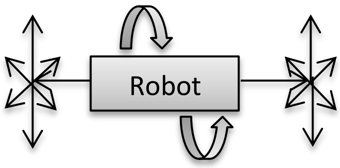
Good maneuverable – do not able to rotate radially, able to take in most of the possible three dimensional turns.



Highly maneuverable – Able to rotate in one radial direction, able to adapt locomotion in most of the possible directions



Excellent maneuverable – Able to rotate in radial directions, able to adapt locomotion in all possible directions.



Therefore, the ranking comparison table with given pints from 0 to 5 from worst to best relatively, which is given in Table 12:

MANE-UVRABILITY	**Not mane-uverable**	**Poorly mane-uverable**	**Average mane-uverable**	**Good mane-uverable**	**Highly mane-uverable**	**Excellent mane-uverable**
POINTS	0	1	2	3	4	5

Table 12: Maneuverability grading

j. Detection Technology

In-pipe inspection robots are equipped with detecting technology such as sensors, cameras, detectors and so on for inspection as the name implies. Each of the sensory devices has a specific task to do. For example, CCD, CMOS, and micro-CMOS cameras are used for the navigation and inspection tasks. Here, CCD cameras require more components than CMOSs, which also brings energy efficiency topic to actuality, which means that in terms of energy efficiency CMOSs are more efficient and less costly than CCD cameras. But, CCD have better resolution than the others which also makes it have more dimensions, bigger in size and less useful in micro-inspection robots for inspecting smaller pipelines. (Shukla and Karki, 2013)

One of the major tasks of in-pipe inspection robots of oil and gas industry is to detect corrosion on-time due to non-wanted chemical reactions occurring risks. Therefore, inspection robot's early stage detection is vital for the industry. However early stage corrosion detection is not applicable by normal modern surface measure techniques as well as vision sensors. It is visible and detectible by thickness measurement of pipeline and structural discontinuities of the pipe wall. By modern technology, there are several advanced techniques to indicate and inspect early stages of corrosion such as Ultrasonic, X-ray, Eddie Current, and Magnetic Flux Leakage technologies. All kind of detection technologies in use and emerging are shown and explained in Appendix C.

X-ray technology is very useful in all terms material detection, from material definition to density estimation and able to inspect almost all materials, however has a huge disadvantage of being operationally unsafe, expensive and lack of closer crack detections and so on.

Whereas, Magnetic Flux Leakage is more applicable in smaller pipelines detection, but cannot inspect all kind of pipeline material. In that sense, Ultrasonic techniques are more useful, where it is a bit expensive to implement and operate. Eddie Current technology is more useful after modern optimization of its technology in higher temperature and it is highly sensitive to magnetic conductivity, permeability and geometrical shapes of the pipeline surface. It is lower in cost and portable for smaller pipeline robots in size.

There is not only inspection for defects inspection, more from that; there are several other applications of inspection robots in terms of detection and other relevant purposes. For example, some robot applications are equipped with gravitational sensors, temperature sensors, humidity sensors, and tactile sensors for different purposes such as navigation and steering. Nowadays, laser projection techniques are also in use for pose estimation and location finding.

As clearly seen, detection technology is also main indicator of robotic development especially for in-pipe inspection robots. Therefore, in ranking and comparing robots due to their detection technology we should classify their efficiency indicators first as following:

Detection technology efficiency indicators:

- Camera technology
- Advanced corrosion detection technologies
  - X-ray
  - Eddie current
  - Surface magnetic
  - Ultrasonic
  - Acoustic
  - Magnetic Flux Leakage
- Main variable sensors
  - Gravitational
  - Length – height measuring
  - Tactile
  - Force
  - Pressure
- Specific variable sensors
  - Stiffness
  - Temperature
  - Material
  - Communication
- Robot's processional sensors

- Pose Sensors
- Joint sensors
- Motor sensors
- Torque sensors
- Etc.

Therefore, proposed ranking point table will be as following:

SENSOR TECHNOLOGY	**No sensors**	**1 subgroup**	**2 subgroups**	**3 subgroups**	**4 subgroups**	**5 subgroups**
POINTS	0	1	2	3	4	5

Table 13: Detection Technology grading

4.1.2 Application of 5-points evaluation method to existing projects

5-points evaluation method is a successful evaluation strategy if weight factors are considered properly for different stakeholders of the development. Each weight factor is chosen due to the interests of interested parties and can be extended. Application of relevant weight factors is discussed in Chapter 5.

In next subchapters, Examples from some of different locomotion methods are chosen. For example, PAROYS-II is gaining motion due to its caterpillar wheels. This is a hybrid type of locomotion which contains both wall-pressed type and caterpillar type drive mechanism.

FAMPER is a wall pressed type – wheeled hybrid type locomotion activated robot. Furthermore, AAPDATFA robot is also a hybrid type wall-pressed robot. Evaluated PIG is a standard example of passive locomotion type. FPIR robot is also a wall-pressed – wheeled-type, but is a small robot with foldable mechanism.

Due to limitations and borders of this work, evaluation method applied to only chosen robots. Later on in this chapter a new robotic design concept is offered, explained and discussed.

a. 5-Points evaluation of PAROYS-II robot

As mentioned in state of the art, PAROYS II is the in-pipe inspection robot with the caterpillar locomotion and unique pantograph mechanism for wall-pressing of Yonsei University in Korea (See in Fig. 18). PAROYS- II was developed to improve upon the in-pipe driving of PAROYS-I, the former in-pipe articulate robot developed for 200 mm horizontal and vertical pipes and ground driving with very less diameter change adaptability. (Park et al., 2009)

Classifications	Specifications
Length	390 mm
Weight	7.8 kg
Adaptable diameter	400-700 mm
Power Consumption	28 W
Maximum Velocity	25 m/min
Communication	RS-232

Table 14: Specifications of PAROYS-II (Park et al., 2009)

α. Working environment ranking

PAROYS-II achieved active adaptability by the pantograph mechanism which is connected with lead screw. Both left-hand and right-hand threads are together on a lead screw as seen in Fig. 45:

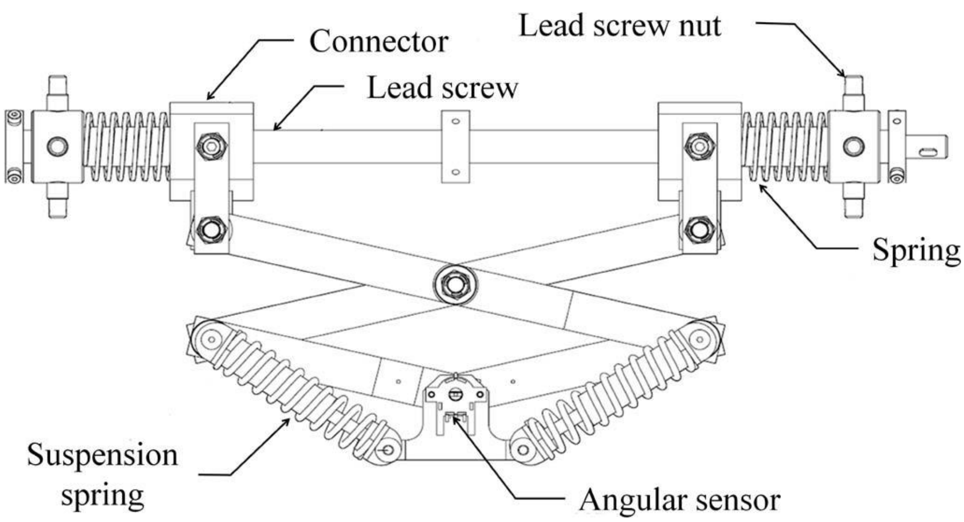


Figure 45: The side view of pantograph mechanism (Park et al., 2009)

Therefore, clockwise and counterclockwise rotation of lead screw causes the left-hand nut and right-hand nut to be closer and farther from each other, respectively. This constitution makes it possible to control the three adaptive modules at the same time. Open ends of the pantograph are pushed by the nuts through two springs and connectors. The springs give some compliance for radial direction movement of the adaptive mechanism. The link length ratio of the pantograph was set at 1:2 to provide the best working range (Park et al. 2009)

The closed end of pantograph is connected with the track module by a revolute joint. Therefore, track driving module can rotate freely. This characteristic help tracks more easily contact with uneven surface or the wall of elbow pipe. It is different with many other in-pipe robots that drive diving modules in literature. (Park et al. 2009)

As indicated the diameter change of the robot mechanism is from 400 to 700 mm. This range is covered in 1 and 2 points in grading scale in Chapter 4.1.1a. Since the Pantograph mechanism is an efficient way for wall-pressing and normal force distribution, the evaluation point in this category is 2.

β. Commercial availability ranking

There has not been found any relevant information regarding PAROYS-II being commercially available. Moreover, the experiments covered in the relevant articles took place in laboratory conditions which is seen clearly. As PAROYS name also indicates it is developed and owned by the university and all open sources are scientific articles.

However, the robot is the second developed prototype of the projects, so it can be considered as more than one prototype. Therefore, the evaluation point in this category is 3.

χ. Autonomy ranking

The robot is fully autonomous in many terms like motion, speed control, force control and so on. It is considered fully-autonomous by the developers. PAROYS-II have efficient use of algorithms and pre-defined path planning, inclination adaptation and diameter adaptation mechanism. However, a control algorithm for fully autonomously obstacle avoidance has not been found yet.

The robot has 4 points in this category.

δ. Energy Supply ranking

The robot can perform with or without a tethered power supply. Although there is not much information about the energy ranking, the robot has few aspects for consideration of energy efficiency. For instance, inclination of a pipeline was considered deeply during the development. It is justified as the problem of energy efficiency rather than a motion problem. On the other hand, the estimation of normal force control thought to reduce the electric power control by controlling the normal force. (Park et al., 2009)

Moreover, a pantograph mechanism is an efficient mechanical solution for pipeline diameter adaptation, with less necessity of using adjusting motors. However, PAROYS-II has plenty of sensors, actuators and other continuous energy-consuming parts due its complex design and control mechanism architecture.

Therefore, the evaluation points for this criterion are 2.

ε. Control mechanism ranking

Control mechanism of the robot intended to focus on posture control, normal force control and inclination of the pipeline. However, a complex motion control and navigating as well as other relevant control strategies have been thought of.

The control unit of PAROYS-II composed of ATMEGA128 and inertial measurement unit, both locates in the central module of the robot. The angle is detected by the potentiometer of the robot which is located in closed end of pantograph. The posture control is done by alignment by velocity control forces the main body aligned in the pipeline. (Park et al., 2009)

The use of angular sensors and the inclination estimation algorithms made the structure of the robot simpler and require less control inputs. (Park et al., 2009)

Use and reaction of those control areas are fully automatized in the robot. Therefore, the evaluation points for this criterion are 4.

ϕ. Production cost ranking

PAROYS-II does not use pressure sensors to control normal force and the pressing force to the wall, it uses mechanical characteristics of pantograph mechanism which can be considered as a cost efficient design. However, the motion architecture is more complex than that. Each driving module has one frontal tracks and two rear tracks. A DC-motor drive the rear tracks with a bevel gear set. Nevertheless, an adjusting motor is shared in adjusting the pantograph mechanism to fit in the pipeline diameter. (Park et al., 2009)

There are a lot of parts and own-designed structure and architecture in the robot, but used in an efficient way. Therefore, the evaluation grade for this criterion is considered 3.

γ. Hydrodynamics ranking

In the development stages of the robot hydrodynamics has not been fully considered and affected the design of the robot. However, due to energy and locomotion efficient design, good hydrodynamics behaviors have been achieved. The robot's smaller central unit, effective pantograph mechanism and having three "legs" gives bigger space to the material flow than similar size in-pipe robots. Of course PAROYS-II designed and tested in laboratory environment and necessary coverings should be done in order to be able to be operated in an in-use case of a pipeline. Keeping this requirement in consideration, the evaluation point would be 3 for this criterion.

η. Locomotion efficiency ranking

PAROYS-II can locomotive in horizontal, vertical, and curved pipes with diameters of 400-700 mm as mentioned in development. The posture, normal force and inclination control gives a big efficiency in locomotion as well. PAROYS-II can navigate easily in pipelines with desired diameters with up to 25 m/min velocity. On the other hand, bi-modular caterpillar wheels' mechanism allows better obstacle avoidance and locomotion in uneven surfaces of pipelines.

Considering efficient but cost-oriented design of locomotion mechanism and taking the effective control architecture into account the locomotion efficiency can be assumed as highly efficient. Therefore, the evaluation points for this criterion are 3.

ι. Maneuverability ranking

The robot can perform many maneuvers due to different speed control of each caterpillar mechanism. This is an effective turning and navigating mechanism. The robot can make easily frontal and reverse motion as well as the turns. Therefore, it can be considered as highly maneuverable, and the evaluation point for this criterion would be 3.

φ. Detection technology ranking

The robot's locomotion is supported by Angular sensors, IMU sensors, velocity and posture control sensors and accelerometer data. With an effective modular design, it can be equipped with any kind of inspection technology. Necessary sensors can be mounted to central unit.

The evaluation points for this criterion are considered 2.

b. 5-points evaluation of FAMPER robot

FAMPER is fully autonomous mobile pipeline exploration robot which is designed as a single module inspection robot for 150 mm diameter pipelines. The robot is developed with four independent wall-pressing type caterpillars driven by two DC-motors each. (See in Fig. 20) The unique feature of the robot is to utilize 4-caterpillar configuration for superior performance in steering and maneuverability within complex pipeline networks and used-case scenarios. (Kim et al., 2010)

The parameter of inspection robot is shown in Table 15:

Classifications	**Specifications**
Length	148 mm
External diameter	127 mm – 157 mm
Pipeline diameter	150 mm
Caterpillar track size	33 mm x 148 mm
Central module	40 mm x 40 mm x 108 mm
Caterpillar track wheels	4

Table 15: Specifications of FAMPER (Kim et al., 2010)

As clearly seen, robot size is small and scalable to be consider as mini-robots. FAMPER has efficient steering capability and is reasonably cost efficient. (Kim et al., 2010)

The main body of the robot consists of the Gumstix board extended by inserting some expansion boards.

α. Working environment ranking

In robot's development four caterpillar wheel tracks are used. To obtain good wall-pressing force and gripping force, as well as to achieve vertical pipes climbing each track is mounted to the main central unit by four independent suspension units. These units are called links and they make sure that given gripping force is enough for the robot. With the help of those links, robot can perform in shape changes as pressing above or pressing under gas pipelines. On the other hand, these links provide robot with active pipeline adaptability. So, it can be generalized that FAMPER can perform in the pipelines with 127 mm as well as with 157 mm. (Kim et al., 2010)

In the projects development aim was to develop a robot which fits and can perform at 150 mm pipelines. In ranking chart it's point is 3, so for this evaluation the point is 3.

β. Commercial availability ranking

The robot was developed in 2010 and there was one prototype available. Since there has not been found any further developments, only one prototype is considered to be available. Therefore, the ranking for this category will be point 1.

χ. Autonomy ranking

Developers are proud of four big achievements with development of FAMPER robot which will be discussed below. However, lastly it is claimed that a very powerful tracking system for handling navigation complications autonomously for better efficiency and autonomy. (Kim et al., 2010) Nevertheless, there is an analog joystick in use with port or Bluetooth connection.

The robot has highs sophisticated control mechanisms designed by using three different languages, in order to gain more autonomy in different pipeline requirements. Therefore, the evaluation point for this criterion is 2.

δ. *Energy supply ranking*

Energy supply of the robot is done by using the Li-Ion batteries inside the pipeline and energy from an auxiliary source. For creation enough torque, each caterpillar robot has two motors attached. The driving power is transmitted to the caterpillar by two geared motors and two pulleys. On the other hand, the main body consists of Gumstix board extended by inserted boards. The board provides interface to microcontroller, compass, 3D accelerometer, rotary encoder and Li-ion battery. (Kim et al., 2010)

Such kind of a design improves locomotion effectiveness and control, however decreases the energy efficiency. Therefore, the evaluation point for this criterion is 2.

ε. *Control mechanism ranking*

As mentioned, Gumstix is used as motherboard in FAMPER development, and although GUMSTIX is a small yet powerful motherboard, it does not contain all other relevant modules for control and communication. Therefore, developers integrated auxiliary boards for expansion with the required communication. Then, they develop a Manual Control Program (MCP) which helps to control and operate FAMPER within inspection. FAMPER Control unit (FC) uses an analog joystick and also provides the flexibility in transmitting control signals by using Bluetooth and USB connectors. It has been programmed on C language for PIC (Programmable Intelligent Computer) microcontroller. (Kim et al., 2010)

Robostix provides the data read from sensors by transferring them to Gumstix after converting the data from analog to digital. WIFI-Stick adds the functionality of data being transmitted. All data is issued in a Linux platform which has the capability of running programs written on high level languages. (Kim et al., 2010)

From control architecture FAMPER has an efficient control mechanism, however degrees of automation are not considered to be high. Therefore, the evaluation point for this criterion is 3.

ϕ. *Production cost ranking*

FAMPER is a very small robot which has but several cost oriented development issues, such as two motors attached in each caterpillar mechanism and there are several unique applications of the robot. (Kim et al., 2010)

However, FAMPER has a flexible extension interface as mentioned for physical actions which gives an option to integrate different sensors and mechanical devices. FAMPER has another feature, such as when one or more sensors are damaged, they can easily be replaced without disassembling entire robot. (Kim et al., 2010)

The evaluation grade for this specific criterion is calculated as 3.

γ. Hydrodynamics ranking

The development for the robot did not consider any hydrodynamic or aero dynamical aspects of development as in other typical applications. FAMPER mainly developed for small pipelines and tested in laboratory environment. However, the geometrical design and four caterpillar wheels does not allow a lot space for hydrodynamics. Therefore, the hydrodynamics would be rated as 1.

η. Locomotion efficiency ranking

FAMPER has an efficient locomotion with independently controlling the velocity and rotating directions of caterpillars. With this feature FAMPER can keep the mobility within any spatial conditions of the pipeline, and with any kind of pipeline fittings. On the other hand, the operational architecture is designed to be simple, which enables flexibility and adaptability for inspection environment. FAMPER is equipped with flexible tracks which increase the gripping force of tracks and robot has ability to be tilted for increasing its contact surface to be able to move in damaged pipelines and to overcome the obstacles. (Kim et al., 2010)

However, the number of motors also increases the costs and consumption which decreases the grade of locomotion efficiency. Therefore, the evaluation point is 3.

ι. Maneuverability ranking

With highs sophisticated independent control of caterpillars, FAMPER can perform almost all kind of turning activities in branches. Robot can perform turning operation in all pipeline layouts as long as at least three caterpillars are in contact with the surface. There can be some cases in pipeline inspection when only two caterpillars are in contact. In such cases, robot can still perform turning operations except only two caterpillars in the diagonal with each other are in contact. If the robot would have self-adjustment capability, where it could arrange three or more caterpillars contacting the surface by self-adjustment of its position, then it could change the direction in T- or Y-branches. However, in straight type of caterpillar mechanism, a self-adjustment capability is almost impossible to integrate. (Kim et al., 2010)

Nevertheless, the robot is able to make forward and backward movements, as well as the turns. So, due to the criterion specifications, robot can be considered highly maneuverable. Therefore, the evaluation point is 3.

φ. Detection technology ranking

FAMPER is equipped with RF-CCD Camera, 3D-acclerometer, compass and rotary encoder. The accelerator performs tilting information determination of the robot, the compass is to access the direction of the robot heading to and the rotary encoder is to measure the distance traveled by the robot. Therefore, the sensors can be divided into two subgroups and the evaluation point for this criterion is 2.

c. 5- Points evaluation of AAPDATFA robot

In-pipe inspection robot with active pipe-diameter adaptability and automatic tractive force adjusting is a unique kind of pipeline robot developed in China. The robot itself has three parallelograms wheel mechanism designed with two-wheel mechanism each as seen in Fig. 38.

Classifications	**Specifications**
Inspection length	1000 m
Weight	Approx. 10 kg
Adaptable diameter	400-650 mm
Tractive force adjustment	1200 N (+/-30N)
Wheel mechanism aperture	120 degrees
Connection	Tethered

Table 16: Specifications of Active Adaptability to Pipe Diameter and Automatic Tractive Force Adjusting Robot(Zhang and Yan, 2007)

The robot is developed for long-distance inspection, of main gas pipelines in different pipeline diameter adaptability. Its geometrical design adopts the shape of 120 degrees apart located two wheeled parallelogram mechanism symmetrically. This design allows robot to realize the pipeline diameter adaptation and tractive force adjustment. (Zhang and Yan, 2007) The specification of the robot is shown in Table 16.

α. Working environment ranking

In the development of the robot an actuator is used to gain the adaptability of pipeline diameter changes as well as tractive force control. As mentioned there are three parallelogram mechanism with two wheels, designed 120 degrees apart from each other and are the exactly same shape and design. Each parallelogram wheel has the front driving wheel and rear driving wheel. The operation of the diameter adaptability is driven by a step motor with convenience to be controlled. This is so called adjusting motor. The adjusting motor drives the ball screw mechanism pair which can push the mentioned three parallelogram mechanism to make wheels to achieve better contact to inner surface of the pipeline as well as to adjust the pressing pressure between the wheels and the wall surface. This is how robot achieves the diameter adaptability. (Zhang and Yan, 2007)

Diameter adaptability is from 400 mm to 650 mm inner diameter of the pipeline. This range is covered in 1 and 2 points in grading scale in chapter 4.1.1a. Since the mechanism is not an efficient way for wall-pressing and tractive force distribution, the evaluation point in this category is 1.

β. Commercial availability ranking

The robot was developed in 2007 and there was one prototype available. Since there has not been found any further developments, only one developing prototype is considered to be available. Therefore, the ranking for this category will be point 1.

χ. Autonomy ranking

The evaluated robot adopted wired tele-operation for technical feasibility, power supply and communication. There is few control mechanisms denoted as embedded computer system in the source, however most of the decisions and planning is taken by the operator in so called engineering vehicle. Therefore, the ranking for this evaluation criterion is 1.

δ. ***Energy supply ranking***

There are few points to be covered in energy consumption of the robot. There are driving motors and adjusting motor, as well as stopper mechanism, sophisticated control mechanism and detection technology and light source which increase the energy consumption of the robot. There is no energy carrier on board so required electricity is supplied by the tethered cable as mentioned. However, developers mention photoelectric convertors on board. Nevertheless, high energy efficiency cannot be mentioned for this type of development. So, the evaluation point for this criterion is considered 2.

ε. ***Control mechanism ranking***

The tether cable, which is composed of two power lines and four optical fibers, is designed by a special technique. Information data and power can be transferred together in this photoelectric hybrid cable. Differed from other optical fiber cables, this cable with excellent abrasion resistance can bear tractive load more than 3000 N. (Zhang and Yan, 2007)

Although, there is embedded control system on board this gives the robot better control efficiency. In control architecture PD and PID controllers, angle, diameter and pressure sensors, encoders and a reliable tractive force adjusting mechanism – algorithm is used.

Thus, control mechanism efficiency will be estimated less since the automatization is less. Therefore, the evaluation point for this specific criterion is 2.

ϕ. ***Production cost ranking***

Most of the parts of the robot are designed specifically for this kind of development. However, not many mechanical – efficient systems are used. Instead, specific sensors, drive mechanisms as well as stoppers are used. For example, to prevent the motor overloading, developers placed a speed reducer with reduction rate of 10:1 between the adjusting stepper motor and ball screw mechanism.

This project has two points in our calculation list. Therefore, the cost efficiency for this specific development is considered 2.

γ. Hydrodynamics ranking

The development for the robot did not consider any hydrodynamic or aero dynamical aspects of development, since it was mainly designed for after use scenarios and when the gas pipeline is not in action. However, if the relevant safety covers would be applied to the robot, the three parallelogram mechanism staying 120 degrees apart from each other gives a high efficiency in hydrodynamics. However, the sensors and camera unit cuts the flow done in this case. Therefore, the hydrodynamics would be rated as 2.

η. Locomotion efficiency ranking

As mentioned in research paper, a wheeled robot with the pipe diameter adaptive mechanism, which can produce an additional normal pressure to change the adhesion force between driving wheels and pipe wall, is capable of adjusting its tractive force in a certain range. (Zhang and Yan, 2007)

While increasing the inspection distance, more tractive force is required, since the friction force and resistance of tethered cable increases and additional kinetic resistance can affect the robot due to changing slope of the pipeline. To overcome those resistances there should be tractive force control mechanism and automatic adjustment. However, increasing tractive force is not sufficient due to the adhesion contributed by the weight of the robot, which can cause insufficient adhesion force and slip of the wheels can occur. To overcome this obstacle as well, developers developed traction force control which comes along with adhesion control to increase the traction capacity. This point is a good development in terms of locomotion efficiency. (Zhang and Yan, 2007)

Therefore, the locomotion ranking is considered 4 for this criterion of evaluation.

ι. Maneuverability ranking

Robot was developed to overcome the tractive force complications and diameter changes, however the size of the robot and geometrical design does not allow the robot to move more than two directions. The robot's diameter adaptability allows the robot to adapt small slope changes and turns, nevertheless, movement in branches could not be considered. The shape and locomotion mechanism of the robot allows steering in slopes and Z shapes in greater diameter pipelines, however the turning and steering in branches could be harder for the robot to perform locomotion and inspection. Since the robot is considered to be poorly maneuverable, and the evaluation point for this criterion is 1.

φ. Detection technology ranking

The robot contains lighting source and classical CCD cameras for visual inspection. Beside, as mentioned robot have pipe-wall thickness sensor, pressure sensor, slope angle sensor, pipe diameter sensor and attitude angle sensor on board. Geometrical shape of the robot allows for development in sensor and inspection mechanism. Detection technology can be classified that the robot has three subgroups of detection technology. Therefore, the evaluation for this criterion of the robot is 3.

d. 5- Points evaluation of Gottsberg Leak Detection PIG

The evaluated PIG is developed in Germany under the company name Gottsberg Leak Detection. The robot is certified and is able to be used under explosion endangered pipelines. The design of the Pipeline Inspection Gauge gives option to the user to change the chasse in order to be able to fit in bigger pipelines for in-pipe inspection tasks. The PIG uses ultrasonic detectors to inspect smaller leakages like 6 liters per hour.

Classifications	**Specifications**
Length	700-900 mm
External Diameter	>=200 mm
Radius curvature	At least 5 x diameter
Battery life	>200 hours
Permissible temp	40-50 °C
Operating Pressure	Max. 100 bar

Table 17:Specifications of PIG GLD (Gottsberg Leak Detection GmbH & Co. KG, 2009)

α. *Working environment ranking*

The PIG is able to process in pipelines bigger than 200 mm diameter. Nevertheless, the pipeline inspection gauge is chasse changeable, and could be used for bigger pipelines up to 1100 mm. However, the first given range is in 150-500 mm of the model evaluation. Therefore, the evaluation point for this criterion is 2.

β. *Commercial availability ranking*

PIGs have higher rate of commercially availability in comparison to other pipeline inspection robots. PIGs are being developed for longer time than the others and there are few PIGs as well as other passive locomotion robots for in-pipe inspection are for sale. Those are on the development stage, mostly are also used in inspections. The specific PIG evaluated are certified and are on sale. Therefore, the evaluation point for this criterion will be considered 4.

χ. *Autonomy ranking*

The PIG proceeds and collects data autonomously. Since the robot moves with the fluid flow of the pipeline, the autonomy of the robot is a topic of discussion, however, the inspection and data collecting is being automatically. Therefore, due to guidelines of this evaluation method the autonomy will be ranked as fully autonomous and the evaluation point is considered 5 for this specific criterion.

δ. *Energy supply ranking*

PIG has a battery inside in order to keep the energy for longer inspection time. It is rechargeable and also available for tethered communication and battery supply. The evaluated PIG uses nickel – metal – hydride battery and alternatively uses nickel- cadmium battery for inspection. On the other hand, PIG does not consume energy in other activities than the function of odometer and mainly for inspection, so it is very energy efficient.

The evaluation point for this category is 4.

ε. Control mechanism ranking

As mentioned, PIG is not being controlled to perform the locomotion actively inside the pipeline. It can be controlled only for the inspection using add-on mechanism which is placed in a pre-determined distance of the pipeline, only to observe and give signal when the pig passes underneath. PIG uses accelerometers and six axis sensors to actively locate the tool, with detecting welding joints along the pipeline. Location accuracy is around 2 m within the first run.

In fact, this evaluation criterion can be considered useless for PIGs. However, within the scope of this work the evaluation point will be considered 2.

ϕ. Production cost ranking

PIG consists of its cover, odometer, acoustic sensors, data collection and processing unit, input mechanism and the battery. All used parts are commercially available products except its certified design. Therefore, the evaluation point for this criterion is considered 4.

γ. Hydrodynamics ranking

Evaluated PIG is designed to be performed in In-use situation. Since the locomotion is passive and PIG can move only with the flow of the material, it should be able theoretically fully-block the material flow. Although the blockage is necessary for the locomotion, the PIG is always a bit small to fit inside the pipeline so the fully blockage is impossible, the evaluation criterion is considered 2 for this evaluation criterion; however, the locomotion efficiency grading will be higher.

η. Locomotion efficiency ranking

As indicated above, the PIG uses material flow and the pressure inside the pipeline in order to obtain driving force. In good situation and prefect fit of the PIG to the pipeline, the robot gains enough tractive force for locomotion. Flow rate is calculated before the inspection and whenever it is not sufficient flow rate can be increased. In very rare cases the pressure is not enough and the PIG can get stuck inside the pipeline. Therefore, the evaluation point is 4 for this criterion.

ι. Maneuverability ranking

Since PIG is able to do locomotion due to the flowing material, the locomotion is possible in only one direction. In some applications, developers use a bi-directional shaft and propeller in order to gain less-efficient reverse driving. However, it is not an applicable issue for the evaluated PIG. Therefore, the evaluation is 0 for this criterion.

φ. Detection technology ranking

The PIGs usually use Magnetic Flux, Eddie Current or acoustic and ultrasonic sensors to inspect the damages and leakages. However, Gottsbergs PIG is equipped with ultrasonic sensors, acoustic sensors, IMU, pressure sensor and accelerometers and an odometer. Gottsberg PIG has the best detection threshold among same tools in the market. However, those sensing technology does not supply real time information and it is a discussion topic to call such PIGs robots rather than inspection tools. Therefore, it is considered to have fewer grades in this criterion and the evaluation point is 1 for this criterion.

e. 5- Points evaluation of FPIR robot

The Flat Pipeline Inspection Robot with two wheel chains is developed by scientists in Korea with unique features like pipeline diameter adaptation in range up to 20 percent, as well as foldable mechanism. The specification of the robot is shown in the table:

Classifications	**Specifications**
Length	80 mm
Weight	237 g
Adaptable diameter	80-100 mm
Total length with cameras	94 mm
Maximum Velocity	8,4 m/min
Communication distance	15 m

Table 18: Specifications of FPIR (adapted from (Kwon et al., 2011))

The wheel chains are arranged with 180 degrees apart from each other so there is flexibility in attaching extra sensors in both sides of the robot. There are two main motors in function; one controls the steering and another one is for driving, as seen in Fig. 46. (Kwon et al., 2011)

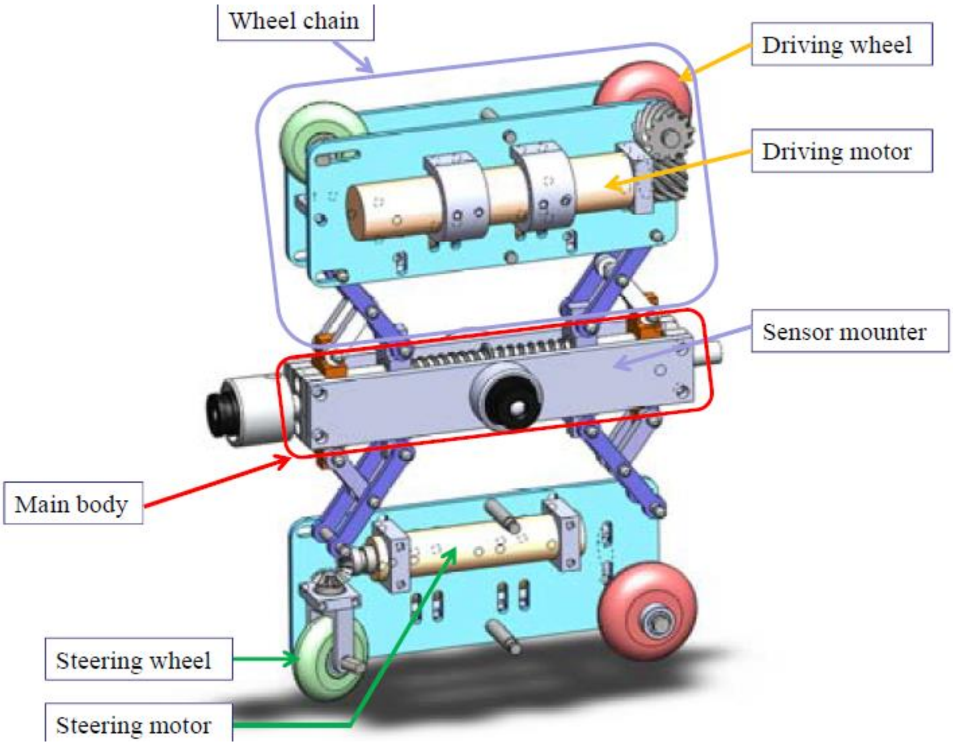


Figure 46: Specifications of FPIR (Kwon et al., 2011)

α. Working environment ranking

The pipeline robot is designed and experimented for the pipelines with diameter up to 100 mm. The key slider or prismatic joint in the main body with four compression springs adapts to change in the diameter of the pipeline. (Kwon et al., 2011)

Mentioned mechanism gives the robot adaptability in diameter change between 80 mm to 100 mm. those range is in 50-150 mm section of the assessment criterion. Therefore, the grade for this criterion is given 3.

β. Commercial availability ranking

The verification of the robot is done with the experiments under a test-bed environment as mentioned in (Kwon et al., 2011). There has not been found any other prototypes or commercially availability source of FPIR. So, due to the evaluation method guidelines the grading should be 1, however having all parts commercially available the evaluation point in this category is 2.

χ. *Autonomy ranking*

Evaluated robot has an easy joystick controller interface and operating module. However, there is some motion planning algorithms already in use in the system. (Kwon et al., 2011) The autonomy of the robot is considered as manually operated, so the evaluation point for this criterion is 1.

δ. *Energy supply ranking*

Robot body does not contain any energy carriage such as batteries. Required energy is supplied through the tethered cable. However, the size of the motors is efficient in energy needed, but the control unit would require much energy.

Therefore, energy efficiency is considered to be stable, since the energy consumption change is avoided by the motors in comparison to the control mechanism, which will be covered in the next subchapters. So the evaluation point for this criterion is 2.

ε. *Control mechanism ranking*

The controller mechanism of the robot and the controller design contains a control box, a control PC, a grabber board and a joystick interface. As mentioned above communication is done by the serial connection with the device and the control mechanism. (Kwon et al., 2011)

Control ranking considers the automation of the control. Since the robot manually operated, however the control of actuators is done by a microcontroller unit, more specifically by Atmega 128, with 128 megabytes of programmable memory and low-energy consumption. Therefore, the evaluation point is considered to be 2 for this specific criterion.

ϕ. *Production cost ranking*

The mechanism is mainly built by commercially available products such as MCU Atmega 128, actuators and so on. Control interface is also supplied by a commercially available joystick mechanism, and a PC controller. Considering the size of the robot, used cable and other equipment's the ranking for this evaluation criterion is 4.

γ. Hydrodynamics ranking

Different from other development projects, developers built FPIR in a flat geometry. The design of the robot intends to have the shape due to better adaptability and detection, however, if the relevant coverage would be used for in-line inspection the geometrical shape is highly efficient in terms of hydrodynamics. Therefore, the evaluation point for hydrodynamics efficiency is 4.

η. Locomotion efficiency ranking

The main body of the robot is linked to the folding mechanism of the mentioned wheel chain. The wheel chain consists of a folding mechanism (parallel linkage), a driving motor, an active wheel, a steering wheel (idle wheel), a steering motor and a steering mechanism which gives the broad range of locomotion options to the robot. (Kwon et al., 2011)

The wheel drive motor drives the active wheel through a helical gear power transmission. The steering motor changes the direction of the steering wheel so that the robot can be steered to a desired direction and the driving speed is calculated as 14 cm per second. (Kwon et al., 2011)

Due to the given information, the locomotion efficiency is evaluated as 3.

ι. Maneuverability ranking

The steering mechanism gives the robot motion in helical form in different directions. Driving wheels and motors system allows the motion in frontal and reverse directions inside the pipeline. However, the steering wheel chains allows robot to make turns and steer inside the branches and changed geometrical shapes of pipelines only in frontal direction. Therefore, the evaluation considers that, the robot has a good maneuverability and ranked with points 4.

φ. *Detection technology ranking*

In the prototype described in the source from 2011, there are three vision cameras of the robot, mentioned as front camera, back camera and side cameras. Frontal camera is a CMOS and provides direct vision to the operator. Nevertheless, the geometrical shape of the robot is designed to be able to have extra cameras or sensors like MT or UT sensor based detection Technology. (Kwon et al., 2011) So, the evaluation of the robot for this criterion is 2.

4.2 Novel design and evaluation of ball-wheeled pipeline inspection robot concept

In this chapter first time in this field a robot with ball wheels will be offered and in addition an innovative design of mentioned robot is presented. This innovative design aims to increase hydrodynamics of the robot to improve locomotion efficiency and maneuverability as well as allowing robot to navigate freely and stable without blocking the pipeline and less affection of the flow during the inspection tasks.

4.2.1 Technical specifications and design of the robot

Following design as seen in Fig. 47 is offered and robotic locomotion with ball-wheels can be adopted, which can offer better maneuverability inside the pipeline against other discussed types. Robot’s design is adopted from the design of a fast subsea turbine and also new wheel concept of one of the biggest wheel producers worldwide.

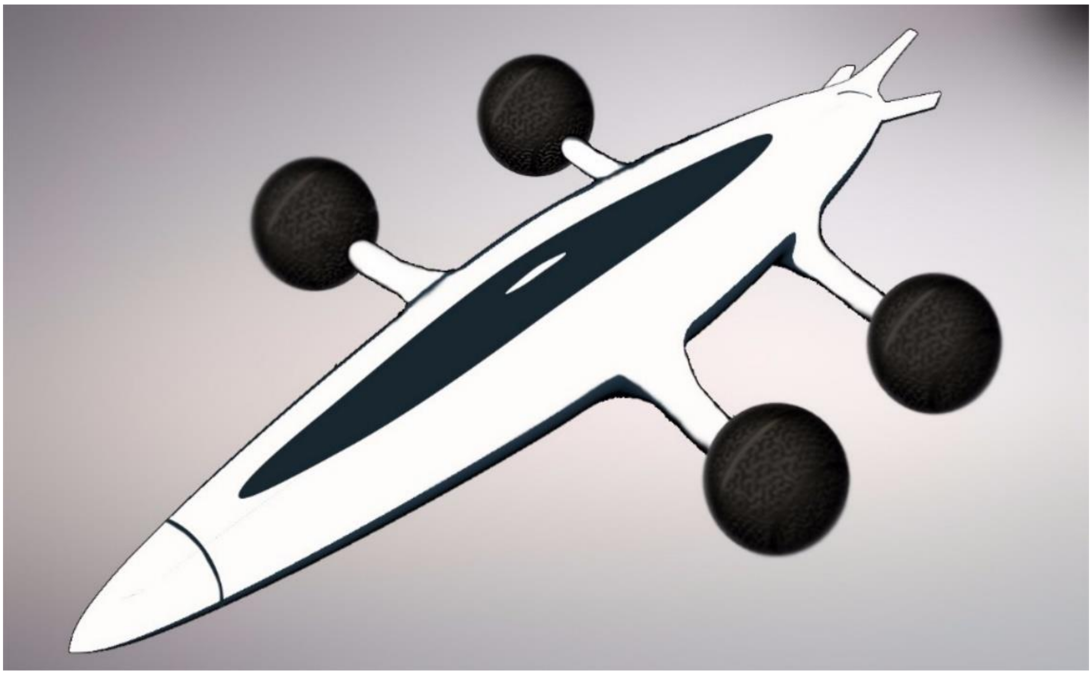


Figure 47: In-pipe inspection robot with ball-wheeled design

As seen in Fig. 47, Ball-wheeled robot has an interchangeable head, which can be adapted to contain several types of sensors, as well as can be changed to a propeller. This body part of the robot is easily adaptable and offers variety of possibilities to the developer and user to adapt the robot to all possible pipeline inspections and for any range of the inspection length. Propeller mechanism will allow the robot to be able to navigate in the opposite direction of the flow, with the help of Double Screw Thread which can be built in robot as deployed in PIG in Fig. 29.

The wheels are ball shaped and can adopt several types of locomotion in different axis. The legs are very flexible allowing robot to navigate freely inside the pipeline and adapt to the pipeline diameter as well as to be able to touch the walls while taking turns and going through L shape pipelines.

The design of tails is able to create vacuum, using the material flow to create extra tractive force for the robot, which increases the locomotion efficiency. Technical specifications of the robot concept can be seen below.

Classifications	Specifications
Length	450 mm
Weight	Approx. 4 kg
Adaptable diameter	Approx. 125-250 mm
Power Consumption	Approx. 62 W
Maximum Velocity	40 m/min
Communication	Tethered/Untethered

Table 19: Specifications of Ball-wheeled robot (Park et al., 2009)

The weight of the concept robot is assumed to be approximately 4 kilograms with relevant batteries and motors.

4.2.2 Evaluation of the robot

As shown in Fig. 48, the ball-wheeled robot concept consists of four main aspects of a novel design. Those main parts are legs, body, head and tail. Ball-wheeled robot legs are out of very flexible spring – plastic material which moves forward and backwards when necessary, in order the ball wheels to achieve better grasping area and higher diameter adaptability. Ball-wheels are the concept design of ongoing researches and developments in the tire industry by Goodyear tires. Body is designed to contain the control mechanism, motors and batteries of the robot inside. It is protected from all sides and the cover is intended to be made out of high-isolation material in order to avoid possible burns and fluid leakages.

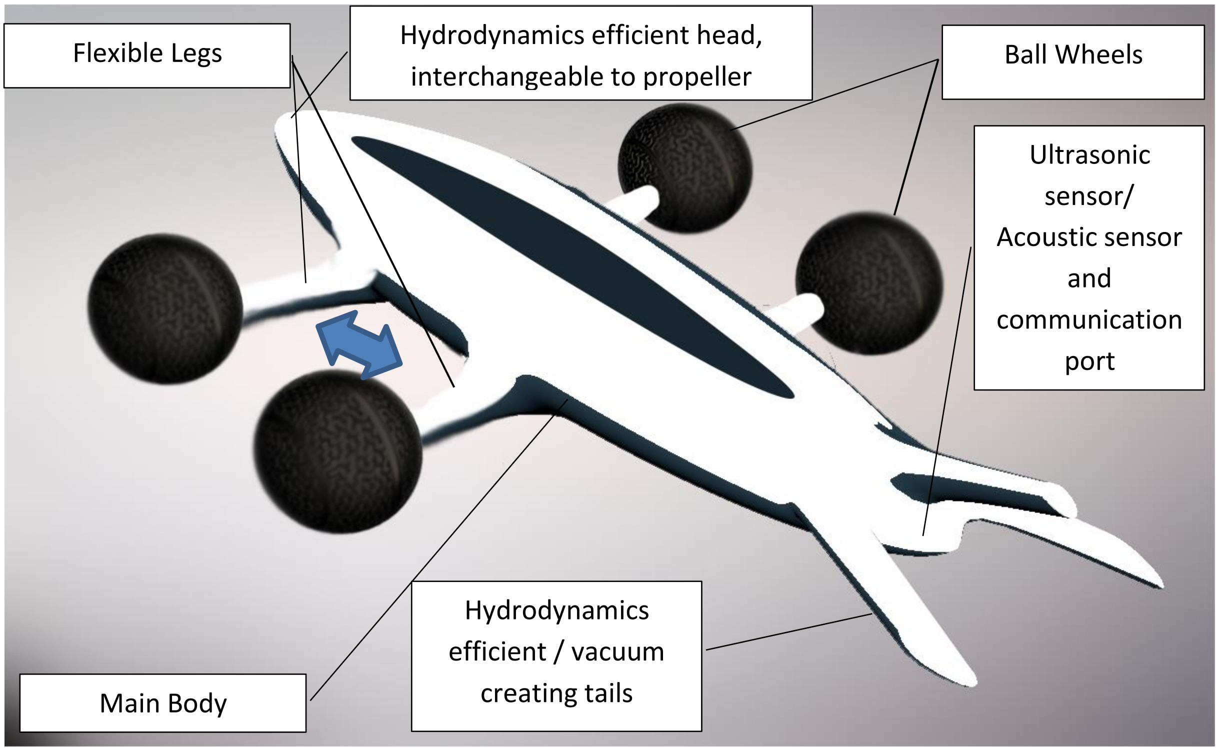


Figure 48: In-pipe inspection robot with ball-wheeled design

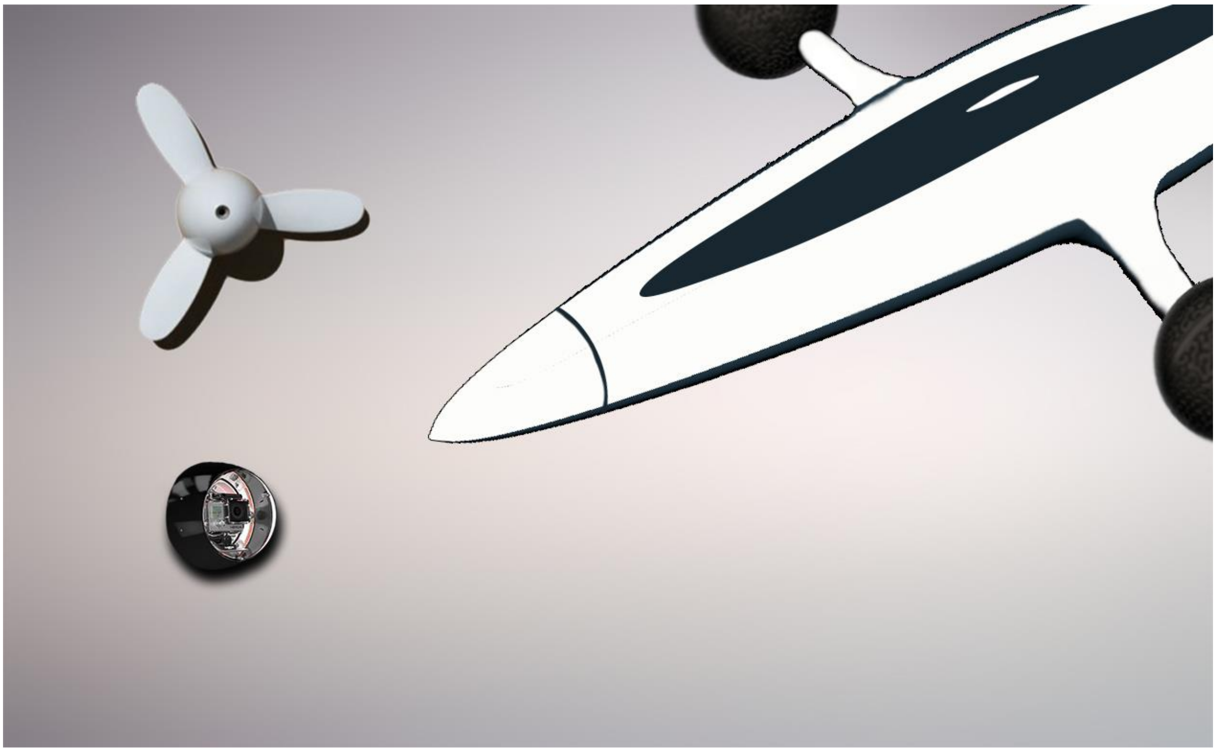


Figure 49: Interchangeable head to propeller or sensor technology

Front head of the robot is designed to be able to easily change from any kind of sensor-deployed heads to a suitable propeller mechanism. Propeller mechanism will be deployed in a need of opposite navigation towards the flow, or in longer inspection tasks for locomotion efficiency or as alternative energy source.

Back end of the robot consist of three tails and a multifunctional port. Tails are designed to increase locomotion efficiency by creating vacuum when swim in a fluid. The port is designed to contain several types of sensors which should be covered and protected those are sensitive to acoustics basically. Port also designed to be able to connect robot with the energy source and to connect to operator during tethered inspection. However, there is a possibility to have battery deployed in the main body of the robot.

Concept design allows robot to be competitive in several aspects with other type of robots in the same area. Detailed evaluation in different criterions is covered in following subchapters.

a. Working environment ranking

Since the working environment specifications are considered to be evaluated due to the radius adaptability of the robot to the radius of pipeline in which ball-wheeled robot will be deployed it ranging from 125 to 250 millimeters, the working environmental criterion can be graded as 3 in this case.

b. Commercial availability ranking

The robot is only in concept phase and in design step, therefore it cannot be considered and evaluated properly for this specific evaluation criterion. However, considering the future developments and fast improvements in this field, conditionally evaluation point will be taken from average 3 points for this criterion for the sake of a fair evaluation.

c. Autonomy ranking

The robot aims to proceed and collects data autonomously. Since the robot will have the ability to move with the fluid flow of the pipeline, the autonomy of the robot is a topic of discussion, however, the inspection and data collecting is being automatically. Therefore, due to guidelines of this evaluation method the autonomy will be ranked as fully autonomous and the evaluation point is considered 5 for this specific criterion.

d. Energy supply ranking

Energy supply of this robot is considered to be in utilizing all possible ways. The robot will be able to perform tethered and energy can be supplied with the cable to the robot. This way of energy supply is thought for the small range inspections of pipelines. However, robot will have on-board lithium or other types of battery to be able to store the electricity energy for processes. Since the robot is able also to deploy a propeller to utilize the flow inside the pipeline to produce energy, the energy efficiency can be considered high.

However, ball wheels and high-sophisticated control and sensor mechanisms will consume more energy than the average robots in this field. Therefore, the evaluation point for this category is 4.

e. Control mechanism ranking

As mentioned, the robot will be fully autonomous and in this case also will have a complex control mechanism, in which most of the decisions will be taken by the robot's control algorithm itself and operator will have option to affect and if necessary to stop the processes and to evacuate. Therefore, the control mechanism ranking is considered 4 points for this criterion.

f. Production cost ranking

The robot is only in concept phase as mentioned in previous subchapters and in design step, therefore it cannot be considered and evaluated properly for commercially availability criterion and for this specific evaluation criterion. However, considering the future developments and fast improvements in this field, conditionally evaluation point will be taken as average for this criterion.

Therefore, the evaluation point for this criterion is considered 3.

g. Hydrodynamics ranking

The design of the robot allows it to be able to move freely inside the pipelines without blocking the material flow. With the deployment of propeller mechanism, the robot is able to even move in opposite direction to the flow. The design of the robot is mainly intending to have the best hydrodynamic behaviors. Therefore, maximum points can be ranked for this criterion and the evaluation point is considered to be 5.

h. Locomotion efficiency ranking

As indicated above, the robot can also use material flow and the pressure inside the pipeline in order to obtain driving force. On the other hand, Locomotion efficiency can be maximized with the help of design of the robot, calculating propeller mechanism and when we take ball wheels' adaptability into consideration. However, some of the branches and obstacles will be hard for the robot to overcome. Therefore, the evaluation point is considered 4 for this criterion.

i. Maneuverability ranking

The ball wheels of the robot give the ability for the robot to move and make maneuvers in all possible directions. Therefore, evaluation point can be taken highest for this criterion. Therefore, the evaluation point is 5.

j. Detection technology ranking

The design of the robot allows the robot to use ultrasonic sensors in the bottom of the robot. In front, the place where propeller can also be easily installed, most of the relevant sensors and cameras can be installed as well. Ball wheels can also deploy the odometer on board, and other relevant sensors such as temperature sensors, processional sensors, and pose sensors and so on can be installed in the main body of the robot. Therefore, the detection technology ranking is considered to have the maximum points – 5 for this criterion.

4.2.3 Evaluation results of ball-wheeled robot

After the evaluation of the robotic concept due to the 5-points evaluation tool Table 20 is obtained.

Robots/Criteria	W/E	C/A	Aut.	Ene.	Con.	Cost	Dyn.	Loc.	Man.	D/T
Ball-Wheeled	3	3	5	4	4	3	5	4	5	5

Table 20: Basic results of ball-wheeled robot

As clearly seen, the overall point of the evaluation is equal to 41, which is so far the best performing robot in the industry. More detailed evaluation outcomes due to the developers, commercials and users of the robot concept will be discussed in the last chapter.

5. Summary and outlook

Summary of obtained results from variable classification and formation will be defined later on within this chapter. However, summary of the evaluation method and outlook of the whole dissertation topics is discussed one after another. To summarize the results of defined 5-points evaluation method, weight factor estimations should be taken into calculation. In order to have better and well distributed results, all stakeholders in this field should be taken into account and all point of views should be covered and considered well. In this work, weight factors of each evaluation criterion is considered due to User, Developer and Intermediary – Commercial representative's positions in development. All concerns and interests are considered as result of discussions and interviews with representatives of all three parties. This is the first trial of such weight factor distribution, however further works should be done on optimizing the weight factors.

5.1 Results and discussions of evaluation method

After the evaluation due to the offered model, we obtain the following basic chart if ball-wheeled robot will also be considered:

Robots/Criteria	**W/E**	**C/A**	**Aut.**	**Ene.**	**Con.**	**Cost**	**Dyn.**	**Loc.**	**Man.**	**D/T**
PAROYS-II	2	3	4	2	4	3	3	3	3	2
FAMPER	3	1	2	2	3	3	1	3	3	2
AAPDATFA	1	1	1	2	2	2	2	4	1	3
PIG	2	4	5	4	2	4	2	4	0	1
FPIR	3	2	1	2	2	4	4	3	4	2
BALL-WHEELED	3	3	5	4	4	3	5	4	5	5

Table 21: Evaluation outlook

As shown in the table, Ball-wheeled robot has also been added to the evaluation. Due to the results obtained from the chart above, sum of the points can be calculated. This basic sum will create a picture of where the robotic developments in in-pipe inspection stand today.

Therefore, the evaluation sum will be as following:

Robots	Total Points
PAROYS-II	29
FAMPER	23
AAPDATFA	19
PIG	28
FPIR	27
Ball-Wheeled	41

Table 22: Evaluation points sum

Table 22 is converted to a visual as seen in Fig. 50 and compared together with Ball Wheeled robot's basic evaluation points. As seen clearly, Ball Wheeled robot has taken the lead with a big difference in between. For this basic evaluation summary, after Ball- Wheeled robot shown in red box, PAROYS-II robot is leading in the ranking. FPIR and PIG perform almost the same, however FAMPER and AAPDATFA is under the average 25 points of the method.

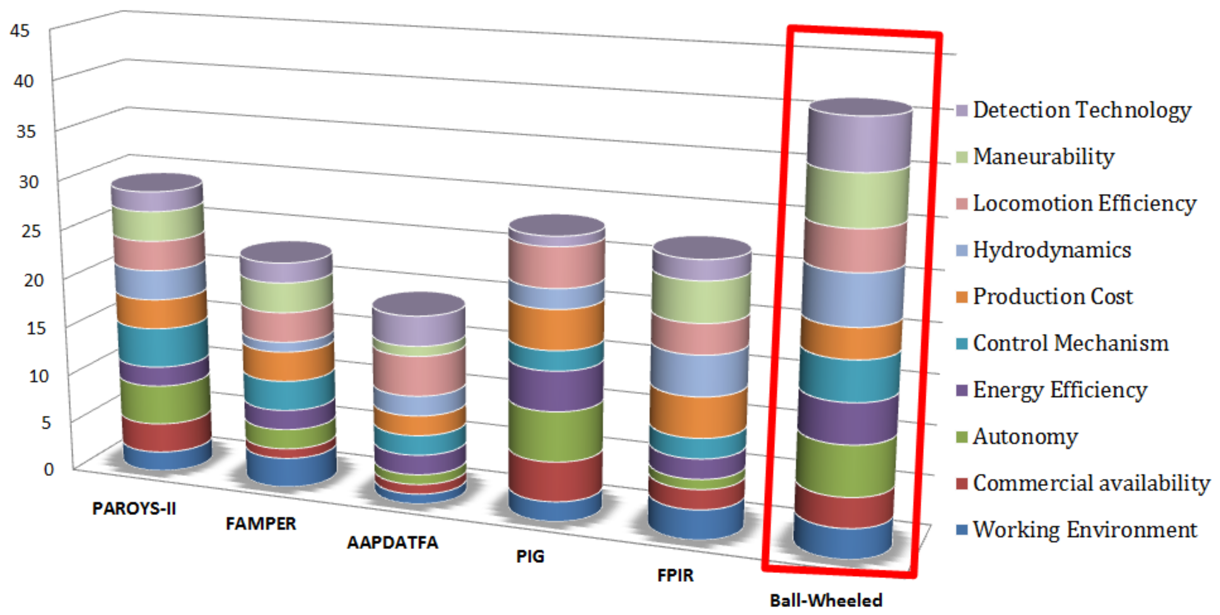


Figure 50: Basic evaluation comparison of robots with ball-wheeled robotic concept

If weight factors would be considered, consideration should be different for the Developer, for the User and for the Seller. The weight factor difference for different stage would be considered as following and separate calculation can be seen in Appendix B

Robots/Criteria	W/E	C/A	Aut.	Ene.	Con.	Cost	Dyn.	Loc.	Man.	D/T
Developer	0,5	1,5	1,5	1	1	0,5	0,5	1,5	0,5	1,5
Commercial	1	1	1	1	1	1	1	1	1	1
User	1,5	1,5	0,5	0,5	0,5	1,5	0,5	1,5	0,5	1,5

Table 23: Weight factor differences due to intended utilization of different people

5.1.1 Results for Developers

From research and development unit's point of view, working environment criterion is not as important as commercial availability, since the development always needs to intend innovation. Autonomy is also an important point for developers, because intention is towards creating autonomous solution. Autonomy should be considered main factor of robotic development in fact. However, energy efficiency and control mechanism importance remain the same for developers. Since cost efficiency is not a primary issue for developers, the weight factor is as same as hydrodynamics. Locomotion efficiency is another crucial point in development, so the weight factor is in the level of other important criterions. Maneuverability is not as important as detection technology for developers; therefore, it has also lesser weight factor than the detection technology. The visualization of weight factor percentages from robot developer's point of view is shown in Fig. 51.

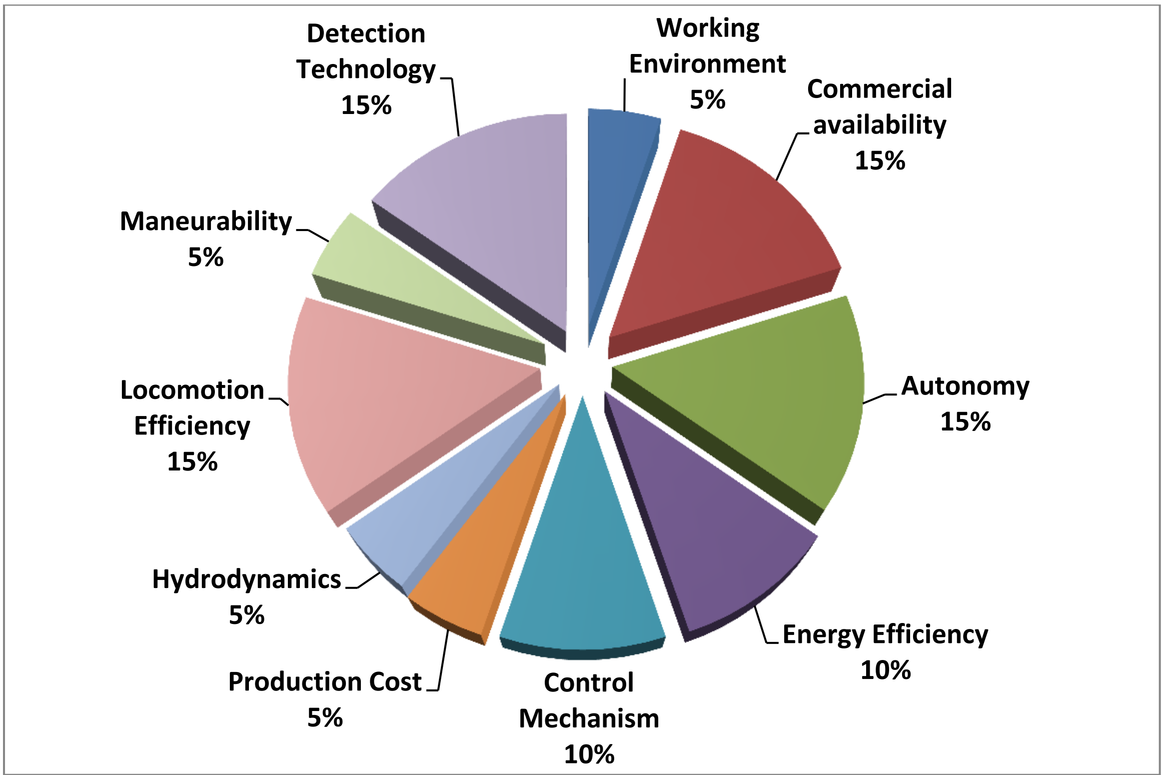


Figure 51: Weight factor distribution of criterions for developers

Considering the weight factor calculations mentioned above and considerations of research and development organizations, following table is obtained:

Robots	**Sum**
PAROYS-II	29,50
FAMPER	22,00
AAPDATFA	20,50
PIG	31,00
FPIR	23,50
Ball-Wheeled	41,50

Table 24: Evaluation sum due to the developer

Due to developer's criterions the results changed completely comparing to the basic chart, since we do not consider Ball-Wheeled concept in the comparison. Ball-Wheeled robot results will be discussed later separately. In the evaluation due to developers, PIG is the leading type of the development with 31 points. So, PIG can be considered best development project for research and development, due to its autonomy and locomotion efficiency. This result confirms one more time that, PIGs are still leading robot type for in-pipe inspection tasks in research and development organizations. Results of the literature review shows the same result for the PIGs, however the evaluated PIG of Gottsberg is highly efficient and useful due to the cutting edge technology and scientific approach of the company. This issue also contributed to the projected results by making PIG leading technological development due to requirements of researchers and developers.

On the other hand, it is expected to have different scenario and different project leading the ranking in evaluation for the commercials, which will be explained in following subchapter.

5.1.2 Results for Commercials

Weight factor application for firms is considered same as the basic evaluation which is covered in Chapter 4. The criterions in the 5-point evaluation has same amount of weight factor due to the commercial point of view. The working environment criterion has same importance as autonomy, cost, availability and energy efficiency, since all of the criterions are main factors for sales. There is a demand for all commercially available and other development projects in all radiuses and conditions around the industry.

Production cost could have higher importance and more weight factor points than the others for commercials, but it is considered same, since such costs will be affected the end-user when purchasing. So, "the cheaper projects sell more than the others" approach is not valid here, since the cost is covered by the user and for commercial firms it is not that important to have cheaper production at least in the discussed field. All criterions are same in the sales, if the demand is considered properly.

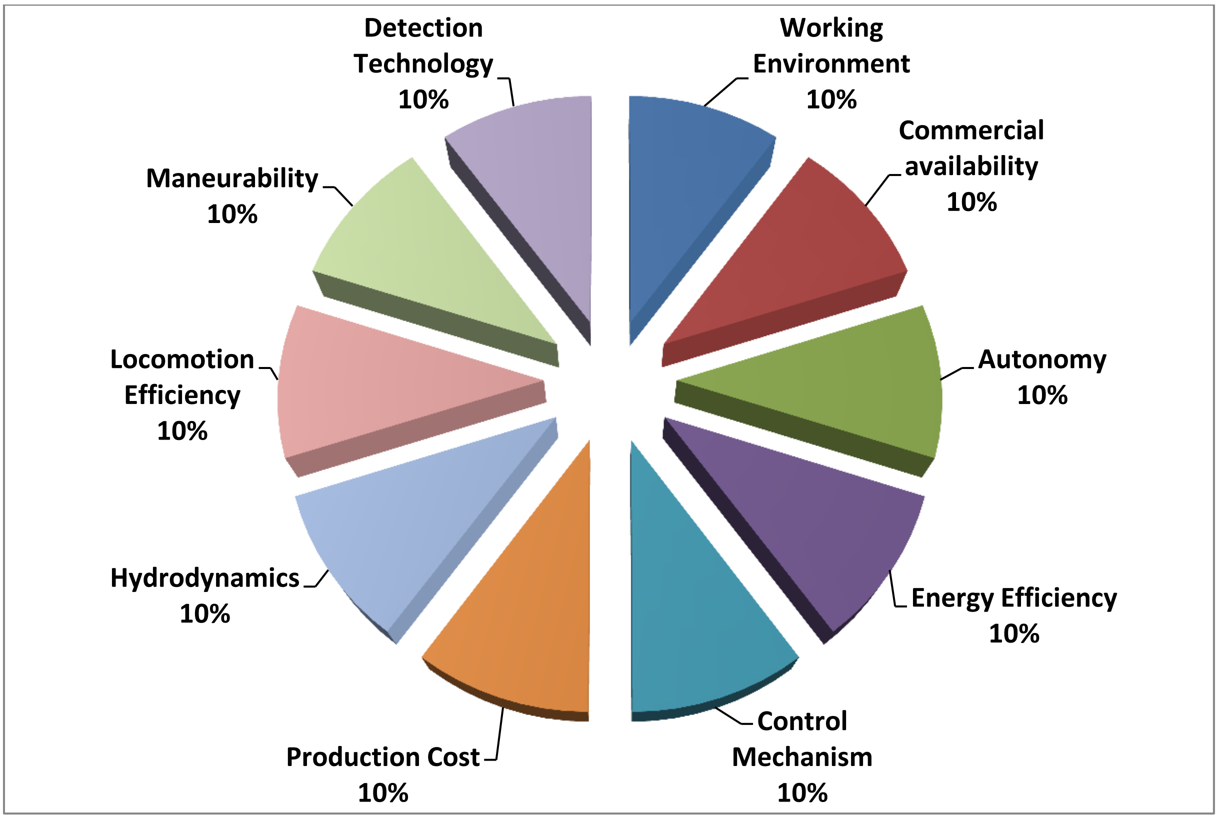


Figure 52: Weight factor distribution of criterions for commercials

Therefore, the weight factors are considered equal for all criterions in the calculation for commercial. So, following chart is obtained, which is same as the basic evaluation results:

Robots	Sum
PAROYS-II	29,00
FAMPER	23,00
AAPDATFA	19,00
PIG	28,00
FPIR	27,00
Ball-Wheeled	41,00

Table 25: Evaluation sum due to the commercial party involved

Ball-Wheeled robot results will be discussed later separately. As seen in Table 25, in the comparison without the Ball-Wheeled concept, PAROYS is leading the rankings and can be considered as the best solution for commercials. However, PIG is till the second best option to sell for the firms. In the evaluation considering weight factors of commercials, FPIR performs well; however, FAMPER is under the average. AAPDATFA cannot be properly considered as one of the best solutions to sell from commercials point of view.

These results projects the expected results as the situation is in the industry. PAROYS is a well-developed and efficient, high adaptive robot, which has more demand in industry. PIG is also a very well-known robot and performs well in sales and other relevant actions for commercials, since it is the best-selling and most-demanding technology in pipeline inspection so far. However, FPIR could be considered also one of the best-selling products if there would be better commercial availability due to its efficiency and other aspects.

It is expected to have other scenario than the discussed cases in the application of weight factors of the users.

5.1.3 Results for Users

The weight factors differ for the users – the inspector's point of view rather than other two stakeholders of the industry. First of all, the working environment and commercial availability are main criterions for users, since the smaller radius pipelines are more dens than the bigger ones, therefore the demand is higher, which creates greater weight factor for working environment criterion than others. Commercial availability is also important and crucial point since the user would access them first and make the decision on existing available and accessible projects. However, autonomy and control mechanism as well as the energy consumption can be considered to have less weight factors, since the inspection takes very small amount of effort and time for the users compared to the daily running business – delivering and transporting the commodity. Hydrodynamics is a topic open to discussion here. There are two types of users in the industry. First type is making the inspection due to the requirements and standards once in each relevant period. And second type is more into operations and is usually involved in bog trans-national pipelines. Here, the relevance of hydrodynamic rise due to the second subgroup. However, considering the proportion of users, first group has been taken as the main users; therefore hydrodynamics relevance is shown less. The distribution of weight factors from user's point of view is shown in Fig. 53.

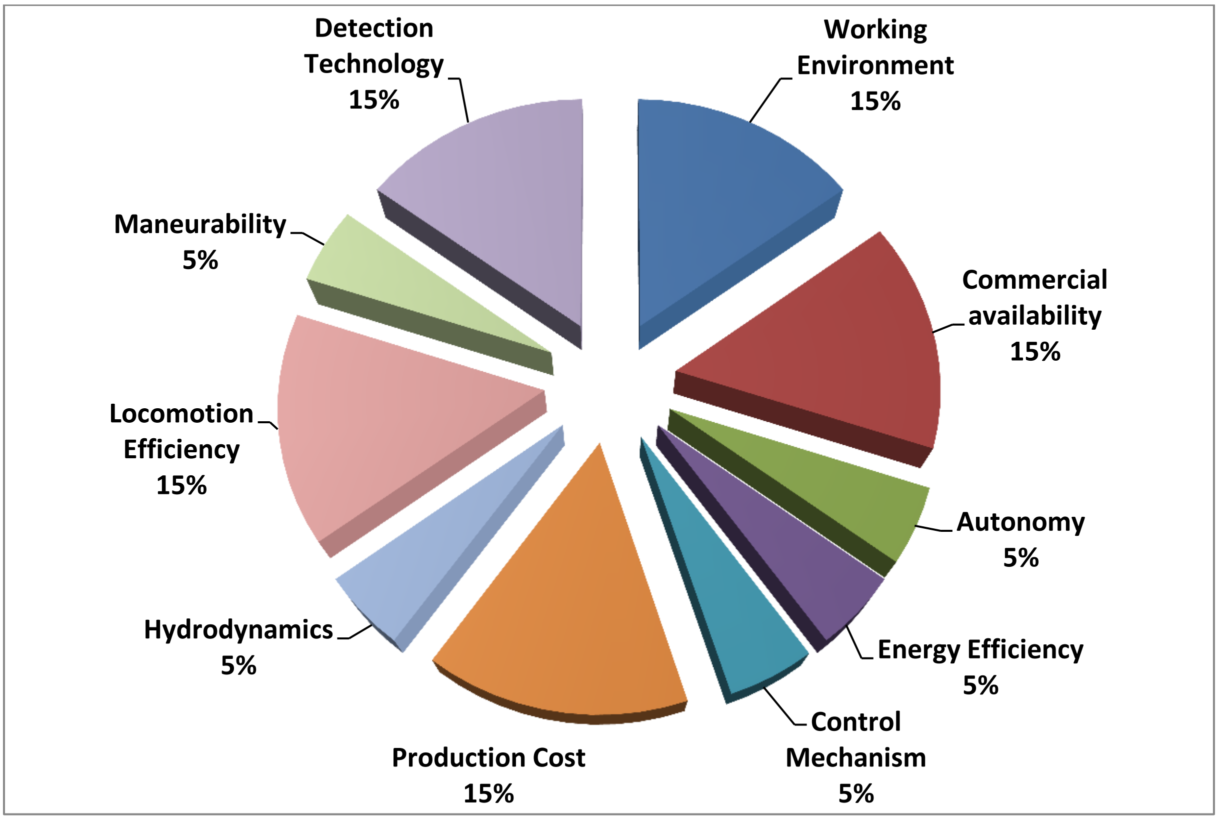


Figure 53: Weight factor distribution of criterions for users

As expected cost is the main decisive element for users in deciding the technology and it is as important as the production costs and detection technology criterions. Hydrodynamics of the robot is considered to have less importance for the users, if the traditional approach is considered in inspection. Traditional approach of inspection aims to stop the flow for the inspection or to use PIGs in inspections which do not affect much the daily processes. Of course the demand of technological developments is to have in-use inspection, but due to the borderlines of this work the traditional approach is followed.

Locomotion efficiency is another crucial aspect of the inspection for users, which means the efficiency in time and more coverage of the inspection. Maneuverability can be omitted and can have the less impact in comparison with other criterions in that sense. But, the detection technology is one of the most asked criterions by users, since the inspector would like to have as much as information possible of the situation of the pipeline with involving less inspection.

With considering weight factor calculations explained above, following table is obtained due to the evaluation sum of the criterions from user's point of view.

Robots/Criteria	Sum
PAROYS-II	27,50
FAMPER	23,50
AAPDATFA	20,50
PIG	29,00
FPIR	27,50
Ball-wheeled	38,50

Table 26: Evaluation sum due to the end user – inspector

Ball-Wheeled robot results will be discussed later separately. From the table above, it is clear that PIG is the most wanted project for the users; however, PAROYS is leading after PIG and has the same value with FPIR robot. The results are not surprising, since the PIG is the most used pipeline inspection robot in the industry currently. On the other hand, FAMPER performed better in this evaluation and is closer to the average points 25.

5.1.4 Discussions

It is clearly seen that PIGs are still widely chosen inspection technology in the industry and it will be the same in the near future till a better technology is on the market. However, the PAROYS and FPIR robots performed surprisingly well in the evaluations. Anyway evaluations differ from different points of views.

One of the main outcomes of the work showed clearly that, none of the existing projects achieved 75 percent of the requirements of stakeholders so far. This is considered to be one of the big achieves in order to have qualitative and quantitative analysis and application of the assessment and evaluation in the industry.

As clearly seen in the tables above, the best performed robot was PIG in developer's conditions and gained 31 points in the grading. 31 points in grading system means completion of 62 percent of the requirements of the industry. 62 percent achievement of the demand as the highest impact of the development can be considered as a very less fulfillment of the requirements. This table shows again the need of improvements and development in the industry.

However, the results of the ball-wheeled robot concept would be different:

Robots/Criteria	W/E	C/A	Aut.	Ene.	Con.	Cost	Dyn.	Loc.	Man.	D/T
Ball-Wheeled	1,5	4,5	7,5	4	4	1,5	2,5	6	2,5	7,5

Table 27: Developer results of ball-wheeled robot

As clearly seen in the table above, the ball-wheeled robot concept gets the best results due to the developer point of view. The overall points are 41.5 which are so far best results achieved by any robotic concept or development in pipeline inspection robot field. Moreover, the score can be converted to 83% by percentage based calculation, which means that such kind of robot would perform 83% out of expectations of a developer.

Robots/Criteria	W/E	C/A	Aut.	Ene.	Con.	Cost	Dyn.	Loc.	Man.	D/T
Ball-Wheeled	4,5	4,5	2,5	2	2	4,5	2,5	6	2,5	7,5

Table 28: User results of ball-wheeled robot

However, the results are not that high if the weight factors of users would be considered. It is only 38.5 points. Nevertheless, it is still best performing robot among other competitors.

Therefore, the overall grade would be 41 points which covers 82 percent of the commercial impact, 83 percent of developers and 77 percent of the users' requirements.

Those percentages would be the best outcomes in the industry are so far comparing the existing projects. Therefore, another suggestion would be to acquire this kind of design in the projects and to carry on further developments for the improving the ball-wheeled robot concept and wide usage of such kind of robot in pipeline inspection.

5.2 Conclusion and suggestions

There are several outputs and conclusion of this work, since it aims to evaluate all the relevant variables, assess the existing development projects, create evaluation criteria for the better evaluation and offer a robust and reliable evaluation method for the industry, apply the evaluation method to existing projects and offer a tool for decision making in in-pipe inspection robot deployment as well as offer a novel type robot as an outcome of the evaluation. All those objectives and research aims take place first time in this field.

As it is visible from the Fig. 54, there are few steps of this work ad from each steps there has been an outcome which can be consider first time in the field. All those steps are towards application of Open Innovation in petroleum robotics as well as to increase the efficiency.

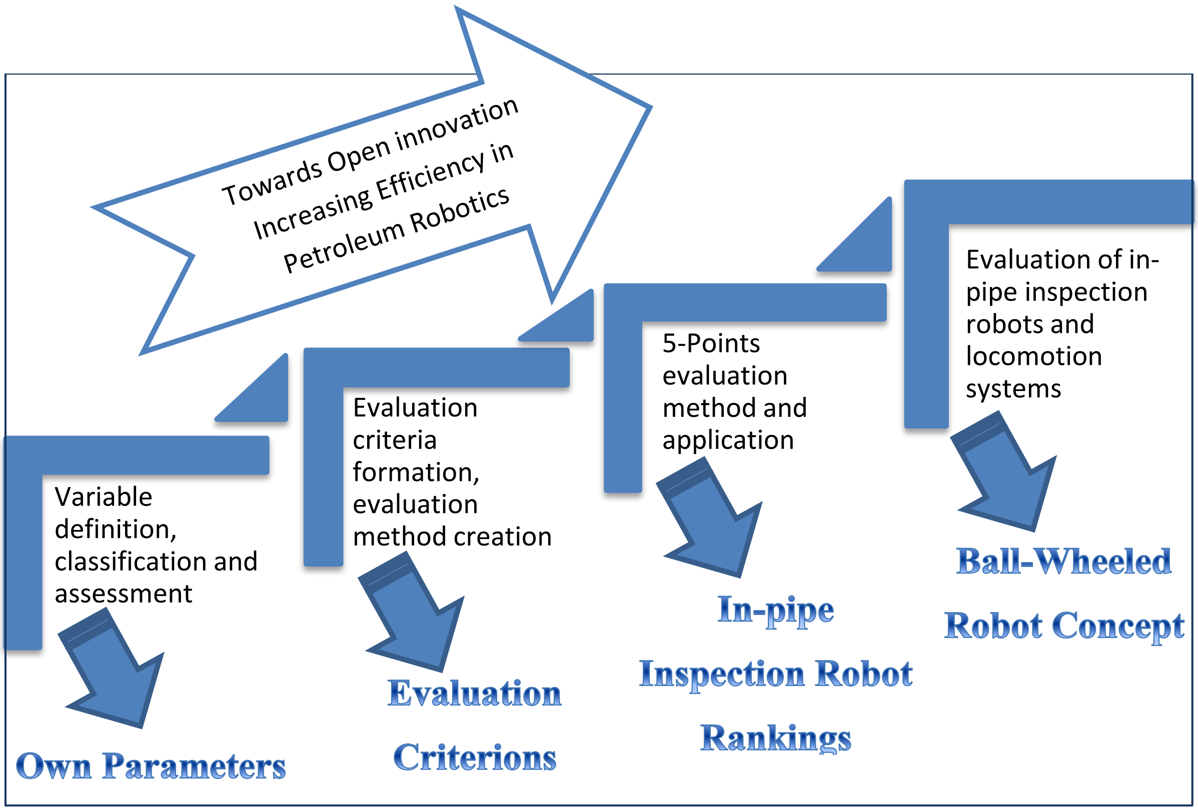


Figure 54: Dissertation improvement ladder and outcomes of each step

5.2.1 Conclusions

First of all, the variable classification and evaluation of possible variables show that there are needs in the industry to have all variables taken into consideration while developing a project. This was a big gap in the development of in-pipe inspection robots. After the first evaluation of the variables, it is figured out that there are several variables which have never been deeply considered in robotic projects of in-pipe inspection research and development.

Those variables are defined as own parameters in Chapter 3.1 and are as following:

S= safety and accessibility of pipeline

$\boldsymbol{\rho_f}$ = density of the fluid inside the pipeline / flow rate

C= temperature inside the pipeline

M= movement directions

Safety and accessibility of the robot should be carefully taken into account in robot development projects, since it defines most of the usage cases of the inspection robot. Without safety and better accessibility of the robot inspections will fail due to tough regulations in the petroleum industry or due to less accessibility of the robot, inspection will stop on the half-way.

Density inside the pipeline is a crucial variable, since it directly affects the pressure inside the pipeline and defines the usability as well as directly affects the locomotion efficiency of the robot. Temperature is not considered so far in the developments; however, is an essential variable which defines specifically the life of the robot in in-use situations, which directly affects the availability and performance of the sensors and actuators as well as the control unit.

Movement directions are another crucial variable that defines the capability of the robots' movement in different directions which is very important in terms of accessibility, inspection range and coverage of the inspection.

Secondly, the variable assessment gives the researcher to have a better evaluation criterion and method which is more robust and reliable than the traditional evaluation methods which is covered in Chapter 2. The variable assessment forms evaluation criterions, which also formed the evaluation method in its turn. The 5- point evaluation method is used in other industries such as in end of life management (Haas, 2012), but has never been used for in-pipe inspection robots.

Formed criterions are well defined and explained as well as positioned in Chapter 4, first time in this field to form better decision making tool for the industry, which is essential to deploy the required technology properly in order to achieve basic guidelines and efficiency in open innovation in petroleum robotics.

The assessment of variables as well as the evaluation method creates the basic necessary platform for Open Innovation to be developed and innovated in the pipeline inspection field first time in the literature. As well explained in Chapter 2, Open Innovation method is the method of future and should be covered and well developed for the sake of better development of the industry and for the innovation management in the oil related fields.

The evaluation method is developed and well explained in Chapter 4 and formed a reliable evaluation framework and can be extended to become a decision making tool in technology management in the industry as well as to create a suitable and useful platform and unifying the needs of the industry towards the Open Innovation transition.

The evaluation tool is applied for the market leading technological developments – robotic projects of in-pipe inspection and obtained reliable results which also projects and confirms the current market needs and market situation which is well explained in the previous subchapter.

However, in the evaluation leading projects were closer to the average points that could be achieved; which mean that there is a huge demand and need for further developments. Since none of the projects fits perfectly to the requirements of neither users nor commercials, nor the developers and the leading technologies still get not many more points than the average in evaluations, it is vital to work on the projects and develop them to fit the key requirements of the stakeholders.

As clearly seen in Fig. 55, different robots perform individually in different weight factor affected evaluation and assessment. Nevertheless, none of the existing robots could perform above 37,5 points. Therefore, it is essential to bring developments further and deploy special type of locomotion systems for developing robots in order to increase usability, durability and sustainability.

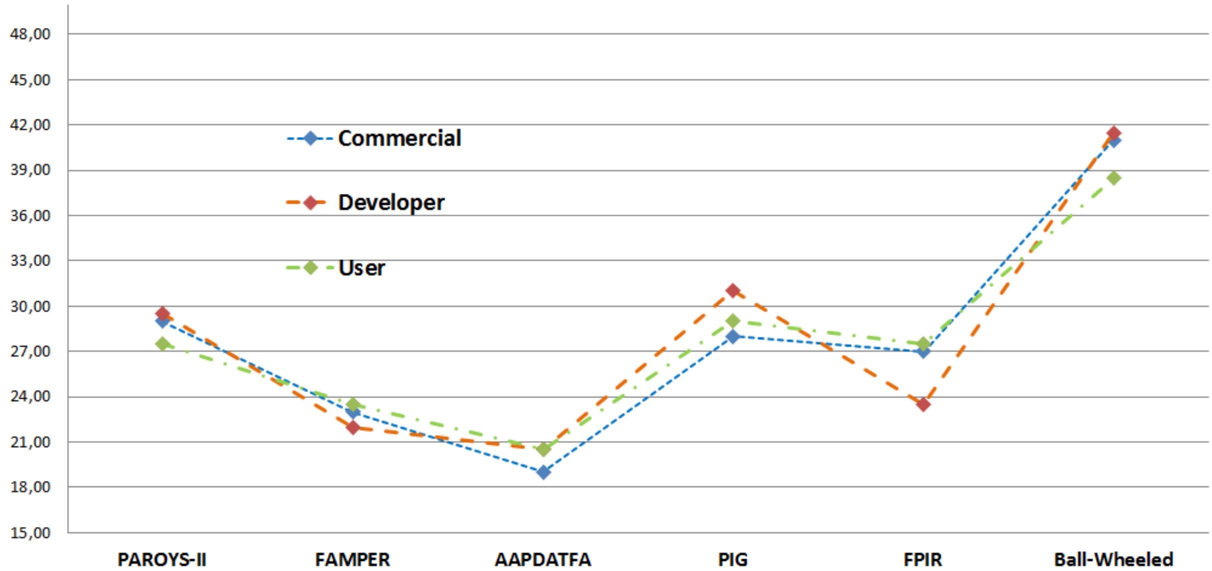


Figure 55: Evaluation comparison of robots due to stakeholders

Another important outcome showed the need of further work in creating better and more reliable tools in unifying the industry in Open Innovation developments and requirements for the technological developments and deployments.

This works concludes the basic evaluation of variables, definition of own parameters, creation of criteria, and formation of 5-point evaluation method as well as the results of application of the method to the existing projects. Conclusion offers to work further in development of Open Innovation platform requirements and improvement of methodologies in the assessment and evaluation as well as variable considerations of the robotic projects, which is out of the scope of this work, but should be done in further researches in order to achieve the research goals.

Another conclusion of this work is justification and equal evaluation of an innovative type of in-pipe inspection robot, which conditionally is being called ball-wheeled robot. It is concluded that such kind of inspection robot would fulfill more requirements of stakeholders than its competitors. There should be further works and developments towards improving the robot and deploying in the industry.

5.2.2 Suggestions

There are few suggestions to be offered as outcomes of the dissertation. First of all, new approaches are necessary in the industry such as Open Innovation platform creations, more work on unification of variables and evaluation methods as well as better understanding on the robotic deployment in the industry.

Out of the work that has been done, it is clear that that there is a demand of improving the work further in developing the variable assessment and evaluation method to be able to apply the Open Innovation efficiency in technological development and robotic deployment of in-pipe inspection robots to obtain a reliable project evaluation tool as well as a decision making tool.

However, it is suggested to work more on the variable setting and to optimize the evaluation method in order to achieve better quantitative analysis in the field.

As another outcome, PIGs are the oldest innovation in the in-pipe inspection field; however, it still leads the fitness of the current industrial requirements; however, it is not the best fit for now, since it does not have the evaluation points more than covering 62 percent in none of the stakeholders' considerations.

In the decision making, 5 – points evaluation method and 10 criterions should be considered and taken into account carefully in both sense: in development of new projects as well as in decision making on robotic deployment.

On the other hand, as first time in the field of in-pipe inspection, the works aimed to evaluate the projects and apply the evaluation method in three different subgroups – the stakeholders of the developments in the industry. The evaluation method applied and calculated due to developers' concerns, commercially involved party's criterions and users' key requirements. Those different groups involved in different weight factors and affected the calculations. As defined in Chapter 5, the results projected trends as of the market today.

Due to the weight factors of different interested groups, it is clear that the PIG is the leading development in the market so far. Which also projects the situation of the industry, since the PIGs are most used robots for in-pipe inspections and GOTTSBERG's PIG is the leading technology carrier in the market nowadays.

Ball-wheeled type robot concept performed at least 20% better in the suggested evaluation method among other development projects in this area. This shows the importance of the developments in this field and it is suggested to go on with the detailed calculations, simulations and prototype development of this specific concept of the robot in the future.

This work was the first attempt in Open Innovation development in pipeline robotics and made first suggestion in variable settings and evaluation tool creation. As another suggestion of this work, a new concept ball-wheeled robot with novel design is offered. However, this was trial of the concept design in this industry and researches and developments should continue in that field.

The much better score for the ball-wheeled approach shows, that for a complete and proper examination of in-pipe inspection robots it is crucial to take all relevant factors into account. This work combines as first one a very complete view of the relevant variable setting, which influences the design and planning phase of in-pipe inspection robotics, with new and common innovation approaches. In addition, through the compared to the literature extended variable set and the other mentioned valuation criterions, this thesis ensures that project and innovation efficiency for the in-pipe inspection robotics setting should rise in the future.

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Appendix A – Table of variable evaluations

Developments / Variables	Locomotion Type	V	P	Ig	Ø	Ob	R	∑F	T	PS	m	M	Φf	C	K	μ	RR	Fl	St	Θ	L	ρf	α	#B	S	B	Com	
Development of an actively adaptable in-pipe robot	Caterpillar	2	1	2	2	1	2	3	3	2	0	0	0	0	0	1	1	0	0	0	1	0	0	1	0	1	2	**25**
Normal-Force Control for an In-Pipe Robot According to the Inclination of Pipelines	Caterpillar	2	1	2	2	3	2	3	3	2	0	0	0	0	0	1	1	0	0	2	1	0	0	1	0	1	2	**29**
FAMPER: A Fully Autonomous Mobile Robot for Pipeline Exploration	Caterpillar	2	1	2	2	3	2	3	3	2	0	0	0	0	0	1	1	0	0	2	1	0	0	1	0	1	2	**29**
Pipe Crawling Inspection Robot: AN Overview	Clamp & Pull	2	1	2	2	0	2	1	1	2	0	1	0	0	0	0	2	0	0	1	1	0	1	0	0	0	2	**21**
Autonomous system for oil pipelines inspection	Clamp - PIG	2	2	0	0	0	3	0	0	3	0	0	1	2	1	0	2	1	0	1	1	0	0	0	1	0	2	**22**
In-pipe inch-worm pneumatic flexible robot	Clamp & Pull	1	0	1	2	0	1	2	0	1	1	0	0	0	0	2	0	0	1	0	1	0	1	0	1	0	2	**17**
An inchworm mobile robot using electromagnetic linear actuator	Clamp & Pull	1	2	0	0	0	1	0	2	1	2	0	1	0	0	0	1	2	0	0	0	0	0	0	0	0	1	**14**
One pneumatic line based inchworm-like micro robot for half-inch pipe inspection	Clamp & Pull	1	2	0	0	0	1	0	2	1	2	0	1	0	0	0	1	2	0	0	0	0	0	0	0	0	1	**14**
Intrinsic Tactile Sensing for the Optimization of Force Distribution in a Pipe Crawling Robot	Crawling	0	0	1	2	3	3	3	3	2	2	1	0	1	0	1	1	0	0	0	1	0	0	2	0	0	3	**29**
“MORITZ” a Pipe Crawler for Tube Junctions	Crawling	2	0	1	2	2	2	3	2	1	2	0	0	1	0	1	1	0	0	0	1	0	0	2	0	0	2	**25**
A Spider-Like Robot that Climbs Vertically in Ducts or Pipes	Crawling	1	0	1	1	2	2	1	1	1	2	0	0	0	0	1	1	0	0	0	1	0	0	1	0	0	1	**17**
A Review: Hybrid Locomotion of In-pipe Inspection Robot	Hybrid	0	1	1	2	0	2	1	0	1	1	1	0	0	0	0	2	0	0	1	2	0	2	0	1	0	2	**20**
Design and Motion Planning of a Two-Module Collaborative Indoor Pipeline Inspection Robot	Hybrid	2	2	2	2	2	2	2	2	2	2	1	1	1	2	1	1	0	0	1	1	2	1	0	0	0	1	**33**
Development of In-Pipe Robot Capable of Coping with Various Diameters	Hybrid	1	0	1	2	0	1	2	0	1	1	0	0	0	0	2	0	0	1	0	1	0	1	0	1	0	2	**17**
Dynamic Characteristics of a Novel Self-Drive Pipeline Pig	Double screw type PIG	3	3	2	0	0	2	3	3	1	1	1	3	0	0	0	1	0	0	0	1	2	2	1	0	0	0	**29**
Intelligent Actuators Realizing Snake-like Small Robot for Pipe Inspection	Snake	2	0	0	0	0	2	1	3	3	1	0	0	0	0	2	2	1	1	0	1	0	0	2	1	1	2	**25**
A robotic system for internal Inspection of water pipelines.	Water Jet	0	3	1	1	0	3	2	1	2	1	1	2	0	1	0	1	0	0	0	2	2	0	0	1	1	1	**26**
Robotic Devices for Water Main In-Pipe Inspection: A Survey	Mixed	2	2	2	2	1	2	2	2	1	1	0	2	0	2	2	2	0	0	1	1	1	1	1	1	2	1	**34**
Design and Motion Analysis of a Flexible Squirm Pipe Robot	Squirm	1	2	0	0	0	1	0	2	1	2	0	1	0	0	0	1	2	0	0	0	0	0	0	0	0	1	**14**

Developments / Variables	Locomotion Type	V	P	Ig	Ø	Ob	R	∑F	T	PS	m	M	Φf	C	K	μ	RR	Fl	St	Θ	L	ρf	α	#B	S	B	Com	
Robotic system with active steering capability for internal inspection of urban gas pipelines	Wheeled	2	0	3	3	2	3	3	1	3	2	2	0	0	0	1	2	2	0	2	3	0	2	3	0	2	2	**43**
Micro Inspection Robot for 1-in Pipes	Wheeled	3	3	3	2	0	3	3	3	3	1	1	0	0	2	1	2	0	0	1	2	0	2	3	1	1	1	**41**
Design of In-pipe Inspection Vehicles for @25,@50,@150 pipes	Wheeled	0	0	1	2	0	3	3	2	2	0	0	0	0	1	0	3	3	3	1	1	0	3	2	1	1	1	**33**
A SIMPLE ARCHITECTURE FOR IN-PIPE INSPECTION ROBOTS	Spiral wheel	2	0	2	2	2	3	0	1	2	3	1	0	0	0	0	2	0	0	2	1	0	2	2	0	0	1	**28**
Development of a steerable, wheel-type, in-pipe robot and its path planning	Wheeled	0	0	2	2	2	2	3	2	2	2	1	0	0	1	1	1	0	0	2	2	0	2	1	0	0	2	**30**
In-pipe inspection robot with active pipe-diameter adaptability and automatic tractive force adjusting	Wheeled	2	2	2	2	2	2	2	2	2	2	1	1	1	2	1	1	0	0	1	1	2	1	0	0	0	1	**33**
Multiconfigurable Inspection Robots for Low Diameter Canalizations	Wheeled	2	1	0	0	1	1	1	2	1	2	0	1	0	1	1	1	1	1	0	0	0	0	0	0	0	1	**18**
Development of an Inspection Platform and a Suite of Sensors for Assessing Corrosion and Mechanical Damage on Unpiggable Transmission Mains	Wheeled	1	2	2	2	1	2	2	1	1	1	0	1	0	1	1	1	1	0	0	2	1	1	1	0	2	2	**29**
Differential-Drive In-Pipe Robot for Moving Inside Urban Gas Pipelines	Wheeled	2	3	1	2	0	2	2	0	2	1	1	0	0	1	1	2	0	1	0	1	1	0	0	1	2	0	**26**
A Flat Pipeline Inspection Robot with Two Wheel Chains	Wheeled	2	2	2	2	1	2	2	2	1	1	0	2	0	2	2	2	0	0	1	1	1	1	1	1	2	1	**34**
Development of an inspection robot for small diameter gas distribution mains	Wheeled	1	2	0	0	0	1	0	2	1	2	0	1	0	0	0	1	2	0	0	0	0	0	0	0	0	1	**14**
Mobility of an In-pipe Robot with Screw Drive Mechanism inside Curved Pipes	Wheeled	2	1	0	0	1	1	1	2	1	2	0	1	0	1	1	1	1	1	0	0	0	0	0	0	0	1	**18**
Modularized In-pipe Robot Capable of Selective Navigation Inside of Pipelines	Wheeled	1	2	2	2	1	2	2	1	1	1	0	1	0	1	1	1	1	0	0	2	1	1	1	0	2	2	**29**
Study of Locomotion Control Characteristics for Six Wheels Driven In-Pipe Robot	Wheeled	2	3	1	2	0	2	2	0	2	1	1	0	0	1	1	2	0	1	0	1	1	0	0	1	2	0	
Research on Key Technology in Downhole Crawling Robot	Wheeled	2	0	0	0	0	2	1	3	3	1	0	0	0	0	2	2	1	1	0	1	0	0	2	1	1	2	
A Study of an Earthworm type Inspection Robot Movable in Long Pipes	Worm	2	1	2	2	1	2	3	3	2	0	0	0	0	0	1	1	0	0	0	1	0	0	1	0	1	2	**25**
sum	**0**	**53**	**45**	**44**	**49**	**31**	**69**	**62**	**60**	**59**	**43**	**14**	**20**	**6**	**20**	**30**	**47**	**20**	**11**	**19**	**37**	**14**	**24**	**29**	**13**	**23**	**50**	**841**
0: Not mentioned not applied, ***1: Mentioned, not applied*** ***2: Mentioned, shallowly applied*** ***3: Mentioned, applied***																												

Appendix B – Tables of evaluation points due to the weight factors

Weight Factors

Robots/Criteria	**W/E**	**C/A**	**Aut.**	**Ene.**	**Con.**	**Cost**	**Dyn.**	**Loc.**	**Man.**	**D/T**	Sum
Developer	0,5	1,5	1,5	1	1	0,5	0,5	1,5	0,5	1,5	10,00
Commercial	1	1	1	1	1	1	1	1	1	1	10,00
User	1,5	1,5	0,5	0,5	0,5	1,5	0,5	1,5	0,5	1,5	10,00

Commercial

Robots/Criteria	**W/E**	**C/A**	**Aut.**	**Ene.**	**Con.**	**Cost**	**Dyn.**	**Loc.**	**Man.**	**D/T**	sum
PAROYS-II	2	3	4	2	4	3	3	3	3	2	29,00
FAMPER	3	1	2	2	3	3	1	3	3	2	23,00
AAPDATFA	1	1	1	2	2	2	2	4	1	3	19,00
PIG	2	4	5	4	2	4	2	4	0	1	28,00
FPIR	3	2	1	2	2	4	4	3	4	2	27,00

Developer

Robots/Criteria	**W/E**	**C/A**	**Aut.**	**Ene.**	**Con.**	**Cost**	**Dyn.**	**Loc.**	**Man.**	**D/T**	sum
PAROYS-II	1	4,5	6	2	4	1,5	1,5	4,5	1,5	3	29,50
FAMPER	1,5	1,5	3	2	3	1,5	0,5	4,5	1,5	3	22,00
AAPDATFA	0,5	1,5	1,5	2	2	1	1	6	0,5	4,5	20,50
PIG	1	6	7,5	4	2	2	1	6	0	1,5	31,00
FPIR	1,5	3	1,5	2	2	2	2	4,5	2	3	23,50

User

Robots/Criteria	**W/E**	**C/A**	**Aut.**	**Ene.**	**Con.**	**Cost**	**Dyn.**	**Loc.**	**Man.**	**D/T**	sum
PAROYS-II	3	4,5	2	1	2	4,5	1,5	4,5	1,5	3	27,50
FAMPER	4,5	1,5	1	1	1,5	4,5	0,5	4,5	1,5	3	23,50
AAPDATFA	1,5	1,5	0,5	1	1	3	1	6	0,5	4,5	20,50
PIG	3	6	2,5	2	1	6	1	6	0	1,5	29,00
FPIR	4,5	3	0,5	1	1	6	2	4,5	2	3	27,50

Appendix C – Summary of current and emerging sensing solutions (adapted from (Glisic, 2014))

Sensing technique	Measured parameters	Continuity of Monitoring	Advantages	Disadvantages
In-line flow metering (for steel pipelines)[a]	Leak detection	Continuous	Simple use	Post-event detection Inaccurate leak localization
In-line pressure metering (for steel pipelines)[a]	Leak detection	Continuous	Simple use	Post-event detection Inaccurate leak localization
Acoustic emission (for steel pipelines and PCCP pipelines)[a]	Leak detection Strands breakage in PCCP	Continuous	Simple use	Large amount of sensors needed to cover entire pipeline
Magnetic flux leakage – MFL (on a 'pig', for steel pipelines)[a]	Defects in wall, cracks, pits, dents, etc.	Periodic	Accurate assessment of pipeline condition	Post-event detection for steel pipeline
Remote field eddy current – RFEC (on a 'pig', for steel pipelines)[a]	Defects in wall, cracks, pits, dents, etc.	Periodic	Internal and external defects	Only periodic inspections are possible
Ultrasonic transducers (on a 'pig', for steel pipelines)[a]	Thickness of pipe wall Defects in wall, cracks, pits, dents, ovalization, etc.	Periodic	Accurate assessment of pipeline condition	Only periodic inspections are possible
Gauging tools with camera (on a 'pig', for steel pipelines)[a]	Internal geometry of the pipeline Defects in wall, cracks, pits, dents, ovalization, etc.	Periodic	Accurate assessment of pipeline condition	Cameras require stopping of transmission in oil pipelines Only periodic inspections are possible
Acoustic and ultrasonic transducers (on a wall, for steel pipelines)[a]	Leakage	Continuous	Accurate detection and localization	Large number of sensors Important cabling needed
Closed-circuit television – CCTV (at manhole, for concrete pipelines)[a]	Internal state of pipeline	Continuous	Accurate assessment	Limited area of observation Small damage not visible
Closed-circuit television – CCTV (on a robot, for concrete pipelines)[a]	Internal state of pipeline	Periodic	Accurate assessment	Used only if not more than 25–30% of pipeline is filled Obstacle in pipeline can stop the robot Small damage not visible

Sensing technique	Measured parameters	Continuity of Monitoring	Advantages	Disadvantages
Sewer scanner and evaluation technology – SSET (for concrete pipelines)[a]	Internal state of pipeline	Periodic	Improved reliability of damage detection 3D imaging	Used only if not more than 25–30% of pipeline is filled Obstacle in pipeline can stop the robot
Focused electrode leak location – FELL (for concrete pipelines)[a]	Leakage Infiltration	Periodic	Accurate detection, localization and quantification	Post-event detection Obstacle in pipeline can stop the robot Applicable only during the dry weather
Ground penetrating radar – GPR (for concrete pipelines)[a]	Bedding of pipeline, detection of scour, rocks, voids etc.	Periodic	Assessment of bedding and evaluation of associated hazards	Performance depends on soil properties Labor intensive
Infrared thermography system – ITS (for steel and concrete pipelines)[a]	Leakage	Periodic	Accurate localization	Complex data analysis
REFC/Transforming coupling (for CPP pipelines)[a]	Detection, localization and quantification of broken prestressing strands	Periodic	Senses beyond inner surface	Manned, non-automatic operation
Wireless technologies (for steel and concrete structures)[b]	Means of reading sensors, computation, and communication	Continuous	Greatly improved coverage of monitoring, data analysis and data management	Power requirement
Distributed fiber optic sensors (for steel and concrete structures)[b]	Strain, temperature, deformation, cracks, leakage	Continuous	High accuracy in measurements, Damage detection and localization High spatial coverage	Installation is labor intensive
LAE (for steel and concrete structures)[b]	Multi-parameter monitoring, strain, deformation, pressure, temperature, corrosion etc.	Continuous	Large area coverage Advantages of wireless technologies	Power requirement Installation is labor intensive

[a] Current technologies.

[b] Emerging technologies.

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