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Sensor-based autonomous pipeline monitoring robotic system

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SENSOR-BASED AUTONOMOUS PIPELINE MONITORING ROBOTIC SYSTEM

Dissertation

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Jong-Hoon Kim
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Abstract

The field of robotics applications continues to advance. This dissertation addresses the computational challenges of robotic applications and translations of actions using sensors. One of the most challenging fields for robotics applications is pipeline-based applications which have become an indispensable part of life. Proactive monitoring and frequent inspections are critical in maintaining pipeline health. However, these tasks are highly expensive using traditional maintenance systems, knowing that pipeline systems can be largely deployed in an inaccessible and hazardous environment. Thus, we propose a novel cost effective, scalable, customizable, and autonomous sensor-based robotic system, called SPRAM System (Sensor-based Autonomous Pipeline Monitoring Robotic System). It combines robot agent based technologies with sensing technologies for efficiently locating health related events and allows active and corrective monitoring and maintenance of the pipelines.

The SPRAM System integrates RFID systems with mobile sensors and autonomous robots. While the mobile sensor motion is based on the fluid transported by the pipeline, the fixed sensors provide event and mobile sensor location information and contribute efficiently to the study of health history of the pipeline. In addition, it permits a good tracking of the mobile sensors. Using the output of event analysis, a robot agent gets command from the controlling system, travels inside the pipelines for detailed inspection and repairing of the reported incidents (e.g., damage, leakage, or corrosion).

The key innovations of the proposed system are 3-fold: (a) the system can apply to a large variety of pipeline systems; (b) the solution provided is cost effective since it uses low cost powerless fixed sensors that can be setup while the pipeline system is operating; (c) the robot is autonomous and the localization technique allows controllable errors. In this dissertation, some simulation experiments described along with prototyping activities demonstrate the feasibility of the proposed system.

Chapter 1

Introduction

1.1 Pipeline

Everything from water to crude oil even solid capsule is being transported through millions of miles of pipelines in the United States. The pipelines are vulnerable to losing their functionality by internal and external corrosion, cracking, third party damage and manufacturing flaws. If a small water pipeline bursts a leak, it can be a problem but it usually does't harm the our environment. However, if a petroleum or chemical pipeline leaks, it can be a environmental and ecological disaster. We can see many US pipeline accidental reports at the National Transportation Safety Board's Internet site [7]. Thus, for keeping pipelines operating safely, periodic inspections are performed to find cracks and damage before they become cause for serious concern.

When a pipeline is built, many inspection methods can be used to evaluate its quality such as visual, X-ray, magnetic particle, and ultrasonic. These inspections are performed as the pipeline is being constructed so gaining access to the inspection area is not problem. Most pipelines are buried except some pipelines like the Alaskan oil pipeline. Once the pipeline is buried, it is undesirable to dig it up for any reason.

Therefore, many remote visual inspection equipments to assess the condition of the buried pipe have been developed. For inspection and recovery action of damaged pipeline, robotic crawlers of all shapes and sizes have been developed to navigate the pipeline. The video signal is typically fed to a truck where an operator reviews the images and controls the robot.

1.2 Motivation and Objective

Proactive monitoring and frequent inspections are critical to maintain pipeline health, as gas, oil, water, and sewer pipelines have become an indispensable part of life. Hence, the continuous proactive monitoring and maintenance system for these pipelines is essential, however, deployment, monitoring, and maintenance of them should remain cost effective, scalable, and easily customizable. A number of technologies, which are proposed and available to monitor, control, and maintain diverse types of pipelines, have still remained in unsatisfying those requirements due to their limitations.

In this dissertation, we aim at designing a cost-effective pipeline maintenance and monitoring system. Such a system would allow frequent inspection, early detection of problems, controllable-error localization, and planned recovery measures. To accomplish those goals, we believe that a monitoring system for pipelines should combine sensor technologies, which are well suited for event localization, and robotic techniques, which allow proactive and corrective monitoring. In addition, we argue that a more efficient technique for locating objects and incidents should be integrated in such systems. Such a technique should use built-in objects that are powerless, easy to add, and densely deployed.

Based on the hypothesis, we have developed a novel method, called SPAMMS (Sensor-based Autonomous Pipeline Monitoring and Maintenance System) in [35], which combines sensor and robotic techniques with radio-frequency identification (RFID) [67] technology for efficient event localization and proactive and corrective monitoring of a large spectrum of pipeline types. Besides providing efficient localization of objects and incidents, our technique have achieved the efficient localization with low cost and controllable errors.

However, the SPAMMS system can be significantly improved by efficient localization technique and enhanced major components; Fixed Sensor, Mobile Sensor, and Robot Agent. Thus, in this dissertation, we firstly propose a RFID-based localization technique, applicable to any kind of pipeline network. It allows controllable localization errors in the sense that the threshold it reaches are controlled by a fraction of the distance separating two successive localization objects. For the fixed sensor enhancement, we secondly propose a new structure for powerless storage using a multiple channeled redundant array of RFID tags (McRAIT [3]) to increase detectability by sensors and agents, storage capacity and fault tolerance of tags and communication. It also speeds up the communication with sensors and agents. For the the mobile sensor enhancement, we thirdly propose the design of a scalable mobile sensor that is able to integrate a number sensing functions, a configurable transmission function, and communication protocol with McRAIT. Scalability allows the sensor to cope with pipeline nature, RFID systems, propagation features, and sensing functions. Configurability allows the sensor to cope with appropriate propagation model. Since the time spent in the pipeline network is relatively short, the sensor we develop allows higher level of processing compared to the available sensor solutions. For the robot agent enhancement, we lastly propose design of a prototype model of an autonomous, topology-aware robot agent with different sensing functions and actuators to perform detailed inspection and react to the detected incidents for corrective monitoring. It uses tilted and segmented caterpillars to allow the robot agent to overcome motion singularity problems that may occur in the pipeline bends (e.g., T-, or Y-bends). We call this enhanced system the SPRAM System (Sensor-based Autonomous Pipeline Monitoring Robotic System) throughout this dissertation.

With the enhancements, we will show the cost effectiveness and scalability of using a monitoring based on mobile sensors, robotic agents, and multiple channeled redundant array of RFID tags for proactive and corrective monitoring of pipelines carrying different materials such as gas, oil, water, or sewer.

1.3 Dissertation Outline

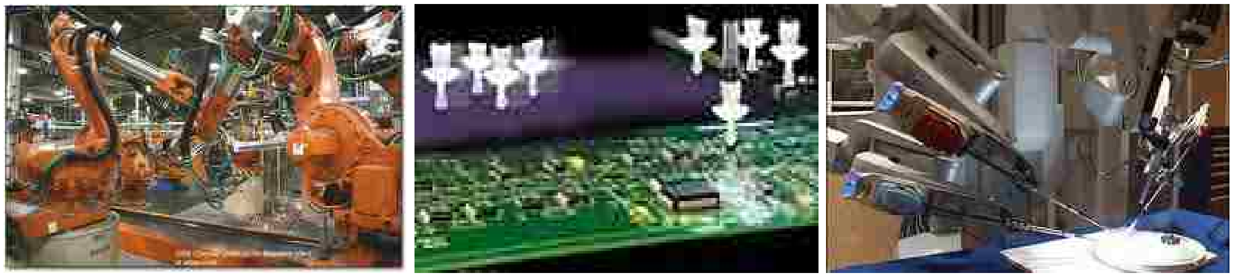
The rest of this dissertation is organized as follows: In Chapter 2, we will give a brief background and motivation of this dissertation study. Chapter 3 will give state of the art on this research field. After Chapter 3, system design will be presented at Chapter 4, then Chapter 5 will introduce the localization technique of the system. Prototyping of the system will be introduced at Chapter 6 and experimental results will be presented at Chapter 7. Finally, we will discuss and conclude this research work in Chapter 8.

Chapter 2

Background

2.1 Robot Domain

An automatically operated machine that replaces human effort was difficult to imagine; in the view of appearance or perform functions in a humanlike manner. By extension, robotic engineering deals with the design, construction, and operation of robots. A robot is a mechanical or virtual artificial agent, which has a brain of its own. In practice, it is usually an electro-mechanical system, which by its appearance or movements conveys a sense that it has intent or agency of its own. There were more than one million robots in operation worldwide in the first half of 2008, with roughly half in Asia, 32% in Europe, 16% in North America, 1% in Australia and 1% in Africa [54]. Commercial and industrial robots are in widespread use, these robots performed jobs with greater accuracy with no labor cost and more reliable than humans. Robots can be placed into roughly two classifications based on the type of job they do. The first category includes tasks which a robot can do with greater productivity, accuracy, or endurance than humans, and the other category consists of doing dirty, dangerous or dull jobs which humans find undesirable. Some examples of different types of robots, which are currently in service, are depicted in Fig. 2.1.



(a) Industrial assembly robots (b) Pick and place robot in electronics assembly factory (c) Laparoscopic surgery robot

(d) Floor cleaning robot (e) Military robot (f) Humanoid robot (Asimo)

Figure 2.1: Different types of robots

2.2 Pipeline Domain

There are many areas where robots can be replaced for human; amongst them pipelines is one of the most challenging areas. Pipelines have been used in major utilities for a long time. Over billions of places, from huge plants to an individual house, robots are employed by people. But, many troubles like aging, corrosion, erosion, cracks and physical damages from third parties, have occurred in pipelines. Therefore, maintenance of pipelines is essential in order to keep them functional, and moreover the continuation cost for these activities are being increased. Even with the above mentioned problems in pipeline, people still prefer them. The reason being, pipelines are used in transporting substances through a mere pipe. Most of the time liquid and gases are sent through pipes. Pneumatic tubes that transport solid capsules using compressed air are also being used. Like gases and liquids, any chemically stable substance can be sent through a pipeline. Hence sewage, slurry, water, and even beer pipelines exist. With this knowledge we can classify pipelines with respect to the substance that it carries. Some examples of different types of pipelines, which are currently in widespread use, are depicted in Fig. 2.2.

(a) Oil-pipeline in Alaska (b) LA aqueduct in antelope valley (c) PVC sanitary sewer pipeline

Figure 2.2: Different types of pipelines

2.2.1 Oil Pipelines

Dmitri Mendeleev, in 1893, suggested pipelines for transporting Petroleum; most countries have employed these pipelines. These pipes started to get widely used around the world. In the year 2007, the total length of oil and gas pipelines in world was almost two millions km, and in the United States had 793,285 km oil/gas pipelines. Pipelines are generally the most economical way to transport large quantities of oil or natural gas over land. Compared to railroad, they have lower cost per unit with higher capacity.

The material used in manufacturing Oil pipes are from steel or plastic tubes with inner diameter typically varying from 4 to 48 inches. Most pipelines are buried underground at a typical depth of about 3 to 6 feet. The oil is kept in motion by pump stations along the pipeline, and usually flows at a speed of about 1 to 6 m/s. Multi-product pipelines are used to transport two or more different products in sequence on the same pipeline. Usually in multi-product pipelines there is no physical separation between the different products. Some mixing of adjacent products occurs, producing interface. This interface is removed from the pipeline at receiving facilities and segregated to prevent contamination. Two of well know oil-pipeline inspection robots, PIGS and SCRAPERS, are depicted in Fig. 2.3.

Oil contains varying amounts of wax, or paraffin. In colder climates wax accumulation may occur within a pipeline. Often these pipelines are inspected and cleaned using pipeline inspection

(a) PIGS pipeline robot (b) SCRAPERS pipeline robot

Figure 2.3: Oil pipeline inspection robots

gauges. There are varies gauges available like PIGS [52] also known as SCRAPERS. These devices are launched from PIG-launcher stations and travel through the pipeline to be received at any other station down-stream; Cleaning wax deposits and material that may have accumulated along the line.

2.2.2 Ethanol Pipelines

(a) Ethanol pipeline in USA (b) Ethanol pipeline in Brazil

Figure 2.4: Ethanol pipelines

These pipelines are majorly used in Brazil and United States. There are several ethanol pipeline projects in Brazil and the United States. Main problems related to the shipment of ethanol by pipeline are its high oxygen content, which makes it corrosive, and absorption of water and impurities in pipelines. Williams conducted an ethanol test in early 1980's. Before the test was conducted; PIGS were used in the pipeline. After the test a few suggestions were made like; frequently dewatering of mainlines using PIGS and spheres, and using closed floater storage tank to prevent rainwater ingestion. Examples of well known ethanol pipelines are depicted in Fig. 2.4.

2.2.3 Hydrogen Pipelines

(a) Hydrogen pipeline in USA (b) Pressure control unit for hydrogen pipeline

Figure 2.5: Hydrogen pipelines

The most cost-effective way to move gaseous hydrogen over a long distance is via pipeline. Hydrogen pipeline is used for transportation of hydrogen through a pipe as part of the hydrogen infrastructure. Hydrogen pipeline is used to connect the point of hydrogen production or delivery of hydrogen with the point of demand, with transport costs similar to compressed natural gas (CNG). Most hydrogen is produced at the place of demand with every 50 to 100 miles an industrial production facility. The 1938 - Rhine-Ruhr 240 km hydrogen pipeline is still in operation. As of 2004 there are 900 miles of low pressure hydrogen pipelines in the USA and 930 miles in Europe. In Hydrogen transportation, pipeline delivery pressure can go up to 700-1,000 psi. Some examples of hydrogen pipelines are depicted in Fig. 2.5.

2.2.4 Water Pipeline

This is one of the most used pipelines all around the world and an ancient method as well. The first people to transport water were the Romans to transport large aqueducts water from higher altitudes by building the aqueducts in graduated segments that allowed gravity to simply push the rushing water along until it reached its intended destination. As time passed by hundreds of pipelines were built throughout Europe and elsewhere, and along with flour mills. The ancient Chinese also made use of channels and pipe systems for public works. The infamous Han Dynasty court eunuch Zhang Rang (189 AD) once ordered the engineer Bi Lan to construct a series of square-pallet chain pumps outside the capital city of Luoyang. These chain pumps serviced the imperial palaces and living quarters of the capital city as the water lifted by the chain pumps were brought in by a stoneware pipe system. We will discuss water pipeline in detail as we go on. *Sewer/Plumbing Pipeline* As we saw that pipelines are useful for transporting water for drinking or irrigation over long distances when it needs to move over hills, or where canals or channels are poor choices due to considerations of evaporation, pollution, or environmental impact. Plumbing derived from the Latin plumbum for lead, is the skilled trade of working with pipes, tubing and plumbing fixtures for drinking water systems and the drainage of waste. Plumbing is a piping system constitutes the form of fluid transportation that is used to provide potable water to their homes and business and also remove waste in the form of sewage. The plumbing industry is a basic and substantial part of every

(a) Water pipeline for farming area

(b) Inside of sewer pipeline

Figure 2.6: Water pipelines

developed economy, due to the need for clean water and proper collection and transport of wastes. A building's waste-disposal system has two parts: the drainage system and the venting system. The drainage system, also called traps and drains, comprises pipes leading from various plumbing fixtures to the building drain (indoors) and then the building sewer (outdoors). The building sewer is then connected to a municipal sanitary sewage disposal system. Where connection to a municipal sewage system is not possible, a local, private, code-approved septic system is required. Cesspools and outhouses do not meet health codes. Plumbing drainage and venting systems maintain neutral air pressure in the drains, allowing flow of water and sewage down drains and through waste pipes by gravity. As such, it is critical that a downward slope be maintained throughout. In relatively rare situations, a downward slope out of a building to the sewer cannot be created, and a special collection pit and grinding lift 'sewage ejector' pump are needed. By comparison, potable water supply systems operate under pressure to distribute water up through buildings. Water systems of ancient times relied on gravity for the supply of water, using pipes or channels usually made of clay, lead or stone. Present-day water-supply systems use a network of high-pressure pumps, and pipes are now made of copper, brass, plastic, steel, or other nontoxic material. Present-day drain and vent lines are made of plastic, steel, cast-iron, and lead. Lead is not used in modern water-supply piping due to its toxicity. The 'straight' sections of plumbing systems are of pipe or tube. A pipe is typically formed via casting or welding, where a tube is made through extrusion. Pipe normally has thicker walls and may be threaded or welded, where tubing is thinner-walled and requires special joining techniques such as 'compression-fitting', 'brazing', 'crimping', or for plastics, 'solvent welding'. Some examples of water pipelines are depicted in Fig. 2.6.

2.3 Navigation within Pipelines

As mentioned above, pipelines have to be well maintained for sustaining their functionality, although their material and structure engineering have remarkably improved for the durability. Moreover, cost of the maintenance has been increased tremendously due to increased length of pipelines.

In addition, most of sewer pipelines are buried or hidden into walls for their protection and hiding their present in the surrounding. Thus, the pipeline accessibility to human for maintenance activities is very limited because many of them are too small to work for human. Even though there are few big once, people don't want to work inside because of dirty as well as hazardous.

(a) Gas pipeline explosion

(b) A city worker tried to unclog a sewer after heavy downpours

(c) Man unclogging sewer overflow, Chennai, India

Figure 2.7: Many troubles in pipeline failure

For example, sewerage water can be overflowed when sewer pipelines are blocked by sludgy or dirty things. In this case, blockages have to be removed from the pipe. Otherwise all areas can be spoiled by dirty water due to outflow. There are several ways to remove these things. First, blocked pipes can be penetrated with a long stick or wire but it is very difficult to do so when pipelines are bent. Second, blockages can be blown out using air pressure, but it doesn't work when pipe have outlets or clacks between the blockage and starting point of air pressure. Third is an excavation of the area which is suspected for clogging (some examples are shown in Fig. 2.7). The difficulty here is a finding clogged area and it also takes long time and large cost. Now we can consider a pipeline robot at this situation. If a pipeline robot can travel, find and remove these things in pipelines, we can significantly reduce the recovery cost as well as time. We can avoid man power for these jobs. Therefore, a pipeline robot can be a strongly recommendable solution for pipeline maintenance.

2.4 Pipeline Robot Classification

2.4.1 Mechanical Classifications

A pipeline exploration robot can be broadly classified into two types namely in-pipe and out-pipe. We can clearly perceive that the out-pipe robots are a little less flexible than the in-pipe robots. Also for the conditions which are being considered in the challenges mentioned above, an out-pipe robot would be an in-appropriate choice, as the prime concentration of our robot agent is to deal with underground or in-wall conditions. So, our robot agent can be classified as an in-pipe robot. Having said that, let us see how the in-pipe robots can be classified into different sub-categories.

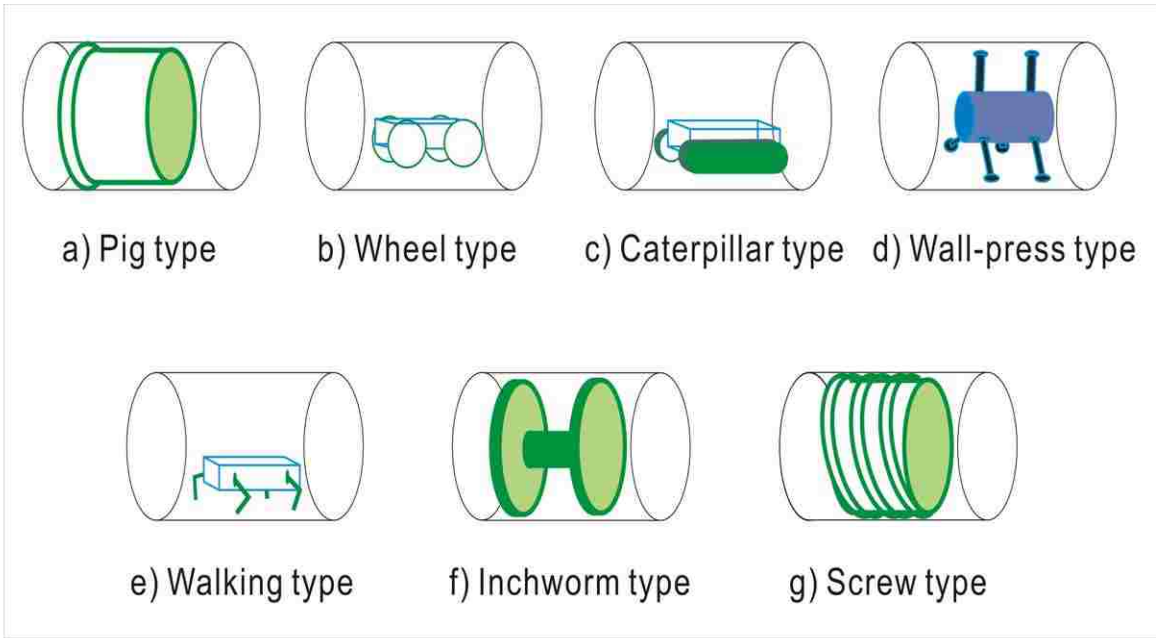
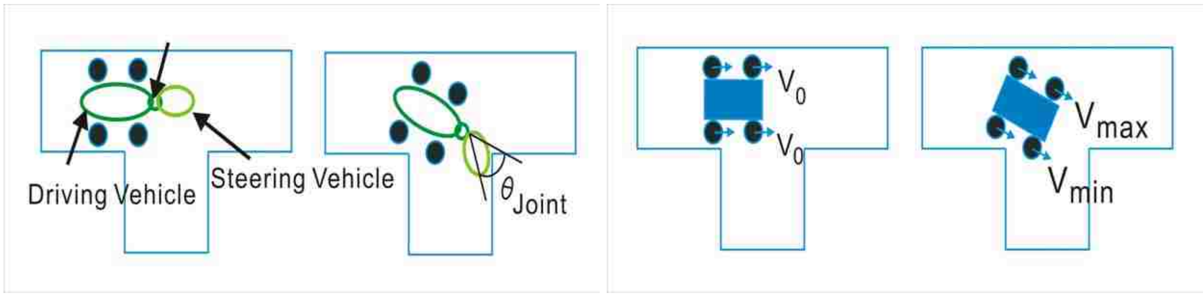


Figure 2.8: Mechanical classification of pipeline robots

With a considerable history behind the development of robotics, in-pipe robots can be coarsely classified into seven different sub-categories, based on their applications. These are named as pig type robot, wheel type robot, caterpillar type robot, wall-press robot, walking type robot, inch-worm type robot and screw type robot. Let us briefly discuss each one of them and their probable applications. Pig type robot as shown in Fig. 2.8(a) is one of the most popular commercial robots, which don't generally use additional driving utilities to move along the pipeline. This type of robot is usually used when there is a sufficient flow in the pipeline, which can effectively aid and drive the robot in phase with the flow in the pipeline. Practically this type of robot is used in pipelines with large diameters [52]. Some modifications have been proposed to this type of robots by adding a propeller that will basically make the robot cope up with the speed of the flow. Wheel type robot as shown in Fig. 2.8(b) is one of the basic types of robots, which is very much similar to a plain mobile robot. And a considerable number of commercial robots have been reported for implementing this specific classification [22] [32] [65] [55]. This type of robot is only applicable in horizontal pipelines. One of the prime ways we could see on how to improve the present wheel type robot is to add more gripping feature to the present wheel type robot. Apparently widening the wheels a little bit and adding a band over those wheels can do this. This type is of a robot is called Caterpillar type robot [56] as shown in Fig. 2.8(c). Caterpillar type robots are usually used in conditions that demand much more grip on the walls of the pipeline. Wall-press type robot as shown in Fig. 2.8(d) is another type of in-pipe robot finding its prime usage in vertical pipelines, which need some adequate force to be exerted on the walls of the pipeline that will in turn prevent the robot from falling down. The advantages of wall-press type robot correspond to the robot with flexible mechanism for pressing the wall by whatever means they apply with [55] [57]. Walking type robot as depicted in Fig. 2.8(e) is a robot with articulated legs that will help the robot in movements that are highly sophisticated [49] [51]. This type of robot usually has a complex design due to its sophisticated motion nature, so this design not usually employed unless the pipeline where this is subjected to demands it. As shown in Fig. 2.8(f), Inchworm type robot does in a way mimic the movement of a worm. Apparently this kind of motion is slow and prefers smaller diameter pipelines [6] [40]. As the motion is slow we cannot implement this model for pipelines that are longer in distance. Last but not the least Screw type robot also called helical drive type robot as shown in Fig. 2.8(g) is named after the motion of this robot [20]. Now that we have seen all the different types of in-pine robots we can have a better prejudice on what features should a given in-pipe robot possess in order for it to be efficient for the job defined. At the same time the robot should perform the required task-space specifications for which it has been designed, like exploring the pipeline. And also depending on the pipeline for which the robot is being designed, we can implement multiple classifications of in-pipe robots, such that the final in-pipe robot will efficiently tackle the complex layout of the pipeline. The pipeline exploration robots existing today can traverse through the horizontal pipelines but only a part of them can work their way out when the pipelines employ some complex layout that avails one or more of elbows (also called L-Shaped bends) and vertical pipelines. And even from those robots which successfully takes care of the previously mentioned layouts, only a few of them will be able to tackle and negotiate the T-Shaped branches.



(a) Articulated active joint type

(b) Differential drive type

Figure 2.9: Typical methods of steering in branch

And a successful implementation of an in-pipe robot demands all these layouts to be handled efficiently, as most of the practical pipeline layouts that exist today employ all these special fittings like elbows, T-shaped branches, vertical pipes, Y-shaped branches etc. in the complete layout of the pipeline structure. Most of the robots described above also employ some kind of a steering functionality in order to make the robot move. Though they employ specific steering procedures, all of these procedures can be broadly categorized as Articulated-type drive and Differential drive types. The articulated-type robot with active articulated joints is similar to those of a snake or annelid type of reptile, which might be most adequate mechanism, even though the steering mechanism becomes complicated to implement for steering joint [28] and double action universal joint [57]. The alternative way of steering is differential drive steering type as shown in Fig. 2.8 (c) and (d), where speeds of all the driving wheels are modulated in order to steer the robot in those special fittings of the pipeline. In order to cope up with all the problems and challenges mentioned above our robot agent, called FAMPER [37] [36], is designed to employ both the Caterpillar type and Wall-press type, so that it will be able to tackle all those special fittings that are used in the modern pipeline layouts and also increases the vertical mobility and enables the driving modules to change directions in the pipeline.

2.4.2 Autonomy Based Classification

Autonomy as the word means by itself leads us to compromise on what different types of sensors, extra hardware and computational equipments we might possibly need to make the robot fully autonomous. Depending on the functionality of the robot, any given robot can be classified as Non-autonomic, Semi Autonomic or Fully autonomic robot.

2.4.2.1 Non-Autonomous Robots

A non-autonomous robot usually just acts as a medium to the human operator to check the subjected area, where the operator cannot reach. The human operator remotely operates the robot, and the control signals for the robot are usually sent through a tethered cable. The human controller determines the conditions of the subjected pipeline by examining the output from the sensor data, which are usually the pictures from the camera attached to the robot. These non-autonomic robots are usually used in commercial plumbing inspection applications.

(a) Tractor L500 with cameraKS200Z

(b) Tractor L100 with cameraKS100

Figure 2.10: Examples of non autonomous robots [RAUSCH Electronics USA LLC]

2.4.2.2 Semi Autonomous Robots

In semi autonomic robots the assessment of the pipeline is not completely left to the human operator. The Robot often includes modules, which will enable the robot to perform actions, which are usually pre-programmed onto the robotic modules. But still the controls to start these operations have to be issued by the human operator. So this makes the robot a semi autonomic. Some of the robots, which show the semi autonomic functionality, are ”PIPAT” [38] [12] developed for quantitative and automatic assessment of the sewage condition. ”Pipe Rover/Pear Rover” [53] developed in 1996 for water-filled pipes and ducts can also be categorized as a semi autonomic robot.

(a) KARO (b) PIPAT

Figure 2.11: Examples of semi autonomous robot

”KARO” [27] uses a tethered cable as a medium to transmit and receive signals from the controller. It was primarily designed for sewer inspection and testing sensory equipment. So all these robots can be categorized as semi autonomic as they do not have the ability to completely perceive the condition of the pipeline without the prompt intervention from a human controller.

2.4.2.3 Fully Autonomous Robots

Fully autonomic robots are one such field where the research and development when compared to the other robots is comparatively fewer than the research being done in other types of robots. A Fully autonomic robot usually carries all the required modules that are required for it to assess and process the condition of the pipeline. These are usually un-tethered robots, so all the control signals are transmitted over a radio link. The control programs that usually run on the on-board computing equipment take care of the robotic navigation and the decisions on the paths to be followed by the robot. And time to time all the status messages are communicated to the human inspector or an Artificial Intelligence unit over the radio link, so that if there are any adjustments that are to be made can be communicated to the robot, so that those adjustments will be adapted by the robot in further actions that will be taken by the robotic controllers. The analysis of the acquired data can be done on the robot itself and/or can be transmitted to the remote inspector for further processing.

(a) MAKRO (b) KANTARO

Figure 2.12: Examples of fully autonomous robots

Only a few of the fully autonomic robots have been developed for pipeline inspection, KURT [21] and MAKRO [15] are two such robot platforms for pipeline inspection that are designed for fully autonomic navigation in more or less cleaned pipelines with diameters ranging from 300 mm to 600 mm, and under dry weather conditions. KURT is able to navigate to ground level pipe junctions, was designed for inspecting pipelines assisted by maps uploaded into the robot. MAKRO consists of six segments connected by five motor driven active joints, these components enable it to simultaneously climb a step and turn in the pipeline junctions. MAKRO was designed to establish that robots can navigate themselves autonomously inside sewer pipelines. KANTARO [46] is another fully autonomous robot designed and developed in Japan for navigating through sewer pipelines with varying inner diameter range of 8-12. But this robot only considers the horizontal mobility and the vertical mobility have been ignored. Although we have quite a few fully autonomous robots for pipelines, none of them guarantee the usage and robustness to be safe and reliable in the pipeline. And most of these robots include complex navigating mechanism and multiple sensors for motion control.

Chapter 3

State of the Art

This chapter gives a literature review of the existing pipeline monitoring systems. We first provide an overview of the sensor-based technologies where mobile sensor nodes are used to assess the quality of the liquid injected in the pipeline. Second, we cover the robot-based approaches for pipeline monitoring and highlight their shortcomings.

3.1 Sensor-Based Technologies for Pipeline Monitoring

Inexpensive and efficient sensing technologies have been designed to provide remote facilities to detect and report the position of any leakage, damage, or corrosion. One can notice, however, that these systems are passive in the sense that they only report on incidents and do not provide tools or agents for incident repairing. The following four major works share this limitation.

A sensor network platform for pipeline monitoring has been developed by Jin and Eydgahi [30] using acoustics sensing devices such as Lead Zirconate Titanate (PZT) sensors. Signals generated by the acoustic sensors propagate along the pipeline and can be used to infer defects in the pipeline such as corrosion. Defects are discovered when the signal generated does not show the cross-correlation values with a reference signal stored for the monitored region. Then, when a defect is detected and identified, an alarm message is sent to the human operator through communication links. Since this solution is based on the transmission and the detection of lamb waves and uses a simple triangulation method based on the time-of-arrival concept, several drawbacks can be noticed. First, the acoustic sensors are customized to the structure of the pipeline, making the solution inappropriate for other types of pipeline technologies. Second, the topology of the pipeline is made very simple, making the localization technique inefficient for complex pipeline topologies.

A wired/wireless sensor network architecture is used by Jawhar *et al.* [29] and Mohamed and Jawhar [41] to provide fault-tolerant communication between sensing nodes fixed to the pipeline and the main control station. The wired part of the network is considered as a primary network, while the wireless part is only used to backup it, in the case of communication failure. While this architecture addresses reliability issues of the wired network, the solution does not include a model providing an optimized management of the energy assigned to sensor nodes and does not integrate clearly a localization mechanism. In particular, nodes close to the control station consume more power than the other nodes since they are likely to be involved in the transmission of all generated data.

Stoianov *et al.* [64] proposed wireless sensor network, called PipeNet, with fixed nodes. It integrates sensors that are able to generate acoustic vibration and collect hydraulic and acoustic/vibration data at high sampling rates. It also provides algorithms to analyze this data to detect and locate leaks. The wireless network is set up to collect events and control the sensors. It also allows every sensor to monitor its local area leak status signal, to detect leakage and locate it via cross-correlation of acoustic/vibration signals. Detection and localization are done through long term sampling and comparing collected data with previously leak-free data, cross-correlating the readings collected by closed nodes, and locating the maximum peak in the cross-correlation. In addition to the drawbacks mentioned for the first work, the uniformity of the liquid characteristics is very important for the efficiency of the location computation.

GASNET [58] is a wireless, self-powered network of keyhole-installed and keyhole-replaceable sensors capable of measuring and communicating key process variables such as pressure, flow, and vibration in natural gas distribution system pipelines. It gathers the distribution network data in real-time at a central control point for monitoring, evaluation, and processing. While the system provide replaceability of the sensors, this system shares the same limitation of aforementioned systems.

Several solutions have been made available to monitor pipelines using mobile sensors. The basic idea in these solutions is to use drifting sensors to: (a) monitor the pipeline, the liquid flowing in the pipeline, and the chemicals generated inside the pipeline; (b) provide close monitoring of the different areas of the pipeline; and (c) generate and transmit event related data when it observes failing statuses (through beacons, for example). The localization of incidents, however, may experience some inefficiencies due to the lack of control of the sensor's mobility or the limits of the communication network attached to the system. Several other limitations can be observed as shown in the following three important works.

A mobile sensor system for mapping water pipelines hidden inside cement walls or under floor coverings, called PipeProbe, has been proposed by Chang *et al.* [10]. PipeProbe works by dropping a tiny sensor capsule into the source of the water pipelines gathering accelerometer and water pressure readings periodically and storing the collected data in its flash memory along with their timestamps. Using these data, the system tries to reconstruct the 3D-spatial layout of the traversed water pipeline. The major drawback of this method is the inaccuracy of the collected data and the uncontrolled correlation between linear and rotational speeds. In addition, the sensors can experience vibrations, which produce noisy 3D accelerometer readings.

Kim *et al.* [33] proposed a low cost, unmanned, fully automated in-sewer gas monitoring system, called SewerSnort. This system uses floating sensors for sewer gas concentration measurement. The floating sensors are introduced at the upstream station and drifted to the end pumping station, collecting location tagged gas measurements. The collected data provides gas exposure profiles to be used for preventive maintenance and/or repair. The localization of events detected by the sensors is based on the availability of fixed beacons set up on the manholes in the pipeline structure. The localization of the defects is simply determined by the identity of the manholes delimiting the segments containing the defects. This generates large errors, needs for more precise localization in the segment, and efforts for continuous power support (for the beacons, for example). In addition, one can notice that the floating sensor's ability to measure the gas exposure is limited because the flow level of the transported liquid, leaks, and dumps in the pipeline may reduce the gas concentration in the vicinity of their locations drastically.

A wireless network system (WSN), which is capable of locating and repairing scale formations in tanks and pipelines within inaccessible environments, for a team of underwater "Collaborative Autonomous Agents" (CAAs), has been developed by Murphy *et al.* [44]. The hardware provided within the CAAs includes appropriate functionalities and wireless communications to detect scale formation in oil pipelines. Every CAA is equipped with a repair actuator to treat the calcium carbonate site with a repair fluid/chemical. While the collaborative work and the location of the quorum signal source is not addressed, this method offers a solution limited to the detection and repairing of very specific scale formations.

3.2 Robot Agent-Based Technologies for Pipeline Monitoring

Robot agent based technologies are considered as an attractive alternative for fully autonomous real-time pipeline inspection and monitoring. These technologies are designed to detect and locate any leakage, damage, or corrosion. In particular, for natural gas distribution system pipelines inspection, Schempf *et al.* [60] proposed the GRISLEE system, which is a set of interchangeable modular elements to perform visual and magnetic flux leakage (MFL) inspection of a live gasmain and repair a weak, leaking or joint-section inside a 4-inch steel live gasmain. The system can be launched through an angled chamber welded to the pipe inside an oversized excavation-hole for the inspection of the pipeline. It can inspect up to 500 to 1000 foot range from a single hole in the pipe if the pipeline is straight and has minimal bends. EXPLORER, again developed by Schempf *et al.* [61], is a long range, untethered, modular inspection robot for the visual inspection of 6 and 8 inch natural gas distribution system pipelines. It can be launched into the pipeline under live conditions and can negotiate diameter changes, 45 degrees and 90 degrees bends and tees, as well as inclined and vertical pieces of the piping network. The modular design of the system allows it to be expanded to include additional inspection and/or repair tools. Although the GRISLEE system and the EXPLORER robot have comparably good mobility in elbows and T-branches, the inspection is cost-expensive and time consuming since the robot is responsible for the inspection of the entire pipeline. Therefore, the inspection can not be performed as frequently as needed. Moreover, the system provides no mean for incident localization, but it only detects and repairs the leaks it detects.

Various other robot agents for pipeline inspection have been made available. Hirose *et al.* [22] proposed several types of robots for the inspection of pipelines with diameter ranging from 25mm up to 150mm pipelines; Tao *et al.* [66] developed inspection robots to detect defects inside the pipeline; Maramatsu *et al.* [43] and Roh and Choi [55] developed pipeline robots to pass through sharp curves inside underground pipelines; Jun *et al.* [31] studied six wheels driven in-pipe robot with the wheels fixed 60 degrees apart in its circumstance; Horodinca *et al.* [24] proposed pipeline inspection robots for 40mm up to 170mm pipelines; and, more recently, Kwon *et al.* [39] proposed a reconfigurable pipeline inspection robot for inspecting 80-100mm pipelines, which works from the collaboration of two separate modules connected by a compression spring.

It is worth noticing that the aforementioned pipeline robots are manually controlled and experience several limitations including the following two facts:

- The topology of the pipeline, where some of them have been used, was made simple and do not have vertical segments and Y- and T-branches;
- The robots exhibit localization problems due to several reasons including wheel slippery, undetectability of the markers.

On the other side, few works have developed semi-autonomous [11] and autonomous solutions [46, 15]. KANTARO, a robot proposed by Nassiraei *et al.* [46], is one of the prototypes of a fully autonomous mobile robot designed for 200-300mm sewer pipeline inspection. It uses a simple moving mechanism, which reduces resource usage and reserves limited computing space for control purposes. Despite this advantage, the techniques developed for the KANTARO to support its localization present some drawbacks due to the limitations of the approximation methods, based on robot wheel rotations, it uses. In fact, a wheel slip can induce large errors on the location computation. The image processing that the KANTARO has added to detect the position of manholes, inlets and pipe joints with the help of blueprint, has only succeeded to reduce this error.

MAKRO, proposed by Rome *et al.* [15], is another robot agent that is fully autonomous, untethered, multi-segmented, and self-steering articulated platform. It is designed for autonomous navigation in roughly cleaned, non-man-entry sewer pipes from 300-600mm at dry weather conditions. A modular approach used to construct the MAKRO gives some advantages to this solution, since it allows to add various equipments by attaching extra segments to the robot. However, the MAKRO's localization technique experiences the drawbacks mentioned for the KANTARO, and it does not have vertical mobility. In addition, some assumptions (e.g., dried pipeline) made by the MAKRO for the operation of the robot are inappropriate for real-time operation [15].

Table 3.1 compares the main characteristics and limitations of the major solutions provided in the literature. This table also compares our solution with them. Our solution is characterized by three features: It is cost effective, in the sense that the agents and the markers, which support localization are cheap and easy to install; it uses RFID systems; and it allows very low range of errors on the position determination of sensors and incidents (e.g; less than 10% of the pipeline diameter). This table, however, does not provide quantitative comparison because of the lack on information about the other solutions.

Table 3.1: Comparison of various pipeline monitoring techniques

				Quality on Localization				
Project	**Active/ Passive**	**Sensing Mode**	**Use of Robot**	**Method**	**Efficiency**	**Cost**	**Auto-nomy**	**Capability of Repairing**
Jin and Edygahi [30]	passive	static	no	signal triangulation	fair (sometime complicated)	high	no	no
Jawhar *et al.* [29]	passive	static	no	Wired Sensor Networks	low (subject to failure)	high	no	no
PipeNet [64]	passive	static	no	signal cross-correlation	fair (not error-free)	high	no	no
PipeProbe [10]	active	mobile	no	beacons and interpolation	low (limited beacons)	high	no	no
SewerSnort [33]	active	mobile	no	RSSI-based beacons	fair (subject to drifter speed)	high	yes	no
Murphy *et al.* [44]	active	mobile	no	RF-based quorum signal	low (depends on detection)	high	yes	limited
GASNET [58]	passive	static	no	sensors position	fair (not error-free)	high	no	no
KANTARO [46]	active	mobile	yes	robot wheel rotations	low (many slip errors)	N/A	yes	no
MAKRO [15]	active	mobile	yes	based on sewer blueprint	fair (map may not available)	N/A	yes	no
GRISLEE [60]	active	mobile	yes	pipe joint location count	low (depends on detection)	high	no	yes
EXPLORER [61]	active	mobile	yes	EM-sonde	low (depends on detection)	high	no	yes
SPRAM System	**active**	**mobile**	**yes**	**RFID systems**	**high**	**low**	**yes**	**controllable**

Chapter 4

System Design

This chapter gives the design of the system. We first provide an overview of the system. Second, we introduce three major components in the system; McRAIT for a fixed sensor, HPMS for a mobile sensor, and FAMPER for a robot agent.

4.1 System Overview

4.1.1 System Requirements for an Efficient Monitoring System

A pipeline monitoring and maintenance system should perform two main activities. First, it inspects pipeline health and reports, regularly, incidents to the control station(s). Second, it helps in recovering the system health from any leakage, damage, or corrosion. Pipelines need to be maintained regularly. However, maintenance costs keep increasing, as well as the scale of pipelines. Thus, a cost-effective and scalable pipeline monitoring and maintenance system should be able to comply with the following requirements:

- **The system should be scalable**: Since most of the pipelines may spread over thousands of kilometers, the system should work for any length and topology of the pipeline. The system should also be independent of pipeline characteristics (e.g., shape, size, material) and topology.

- **The system should be easily customizable**: With minimal activity and modification, it should be a generic solution to cope with different applications, such as monitoring the health of a large variety of pipeline types. It should allow the integration of sophisticated general purpose sensors.

- **The system should be dynamic**. The system should include capabilities and software allowing dynamic inspection of the pipeline and real-time reaction to problems as they are detected. It should provide robust performance to cope with the variability of problems that may occur.

- **The system should provide proactive monitoring and recovery actions**: The system may be able to find any defects in the unhealthy pipeline under monitoring before failures happen. It should be able to properly analyze the incidents and provide rapid recovery actions.

- **Major components of the system should be autonomous**: The major components of the system should work independently and collaborate. They should not be manually controlled while executing their tasks. They should not rely on external energy and should have sufficient energy to perform their duties.

- **The system should be cost-effective**: The system should lower the deployment, operational, and maintenance cost of pipeline monitoring and maintenance. To achieve cost-effectiveness, system components should be low power general purpose tools, be capable of transferring and receiving event-related data, and be able to perform simple physical actions.

- **The energy consumption of the system should be minimized**: The system components should provide efficient communication and data transfer activities with low energy consumption. Actions involving information management, computation, and recovery should be optimized.

- **The system should implement efficient localization techniques**: Efficiency requires that entities involved in the inspection and incident discovery within the pipeline should be able to locate incidents (and themselves) with controllable errors.

4.1.2 High-Level Description of the System

The SPRAM System we propose in this dissertation is based on a novel set of techniques which combines sensing technology, RFID systems, and robot agent technology for a proactive monitoring and localization of events in different types of pipelines. It has three major components.

The first component of the SPRAM System is the multiple channeled redundant array of independent RFID tags (McRAIT) system. It is implemented by a passive RFID (Radio Frequency IDentification) system as they do not require manual inspection or optical scanning and are inexpensive. The McRAIT system uses multiple tags and multiple frequencies to improve storage capacity, McRAIT detectability, and tolerance to loss of information. Each tag in the array is allocated a specific radio channel, as depicted in Fig. 4.1, so that all tags in the array can be accessed simultaneously. The McRAIT system is used to provide mobile sensors with location information within the pipeline topology. The installation of multiple tags used in the McRAIT system can be performed initially (at the construction of the pipeline) or when needed by the pipeline operation. In the latter case, the robot will be used to set up the needed McRAITs. As McRAITs are very inexpensive and need no power, they can be very close to each other. The information stored in an McRAIT can be read by any mobile sensor or robot agent in the vicinity of that McRAIT.

The second major component (depicted in Fig. 4.2) of the SPRAM System is a High Performance Mobile Sensor (HPMS) which is equipped with different kinds of inspection capabilities. Those capabilities, when attached to a mobile sensor, allow it to play different roles simultaneously, including visual sensing, chemical sensing, pressure sensing, and sonar sensing. The selection of specific sensing functions to attach to a mobile sensor are determined by the material carried by the pipeline and the nature of the inspection. The mobile sensor implements a modular architecture integrating an RFID reader and writer for reading and writing RFID tags, and for localization and communication. The main advantage of mobile sensors used in the SPRAM System is their immunity to pipe profile. They are neither sensitive to the pipeline materials nor dependent on the

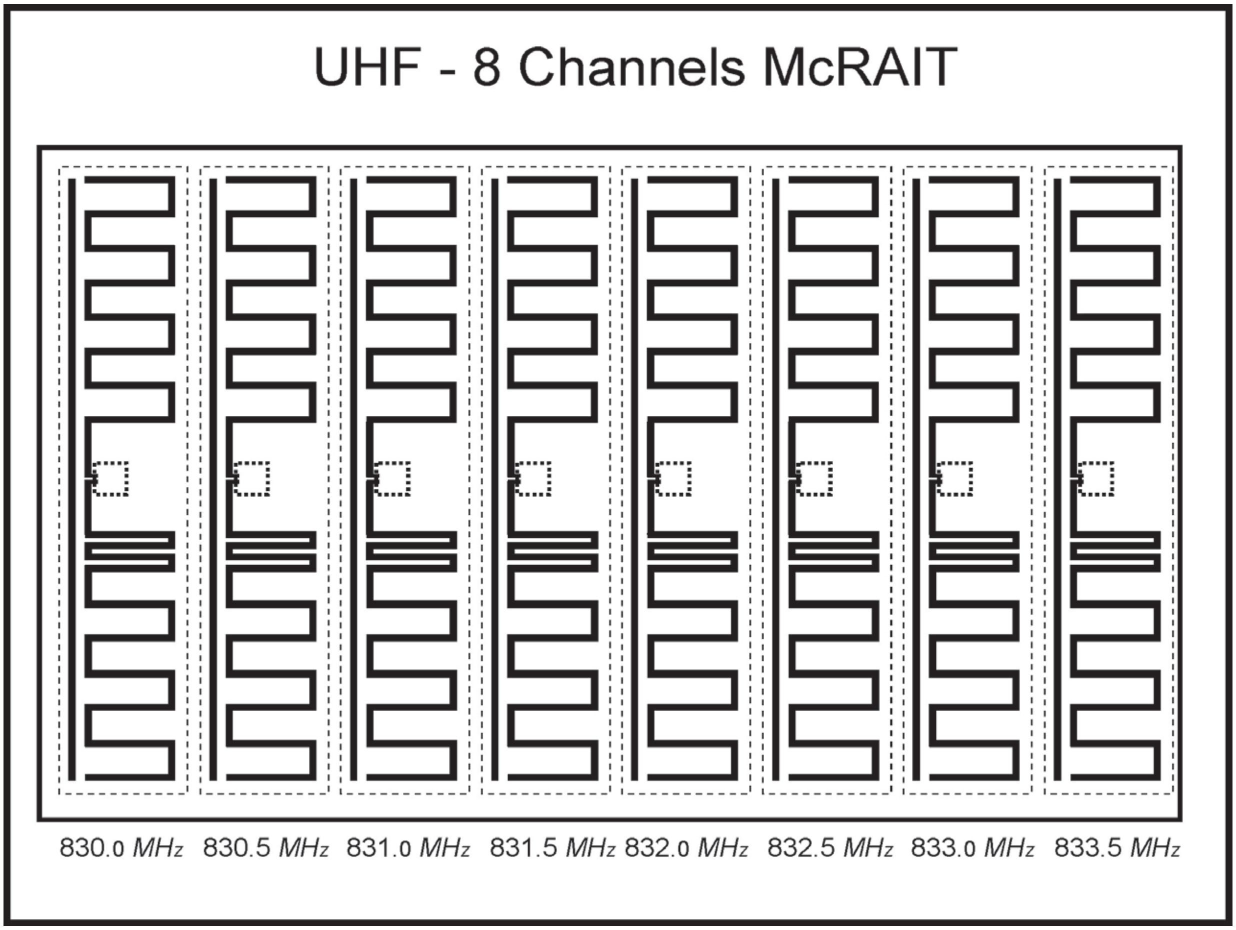


Figure 4.1: McRAIT system design

shapes of the pipelines. They can also operate during low flow rate conditions.

In the beginning of the inspection, a set of (redundant) mobile sensors is deployed at strategic locations (nearby the upstream station or at intermediate outlets). Once they are deployed in a pipeline, the fluid transported by the pipeline will provide sensor mobility. The mobile sensors examine the pipeline using different sensing functions in their course and report the objects and incidents identified to the McRAIT system that is close to the incidents. The McRAIT system helps in determining the mobile sensors position by letting its tags serving as markers. After the inspection completion, the mobile sensors are collected at the exit point of the pipeline. The central controlling system post-process the information collected by them for detailed examination.

The third major component of the SPRAM System (as depicted in Fig. 4.3) is the Fully Autonomous Topology-aware Mobile Pipeline Exploration Robot (FAMPER). It performs detailed

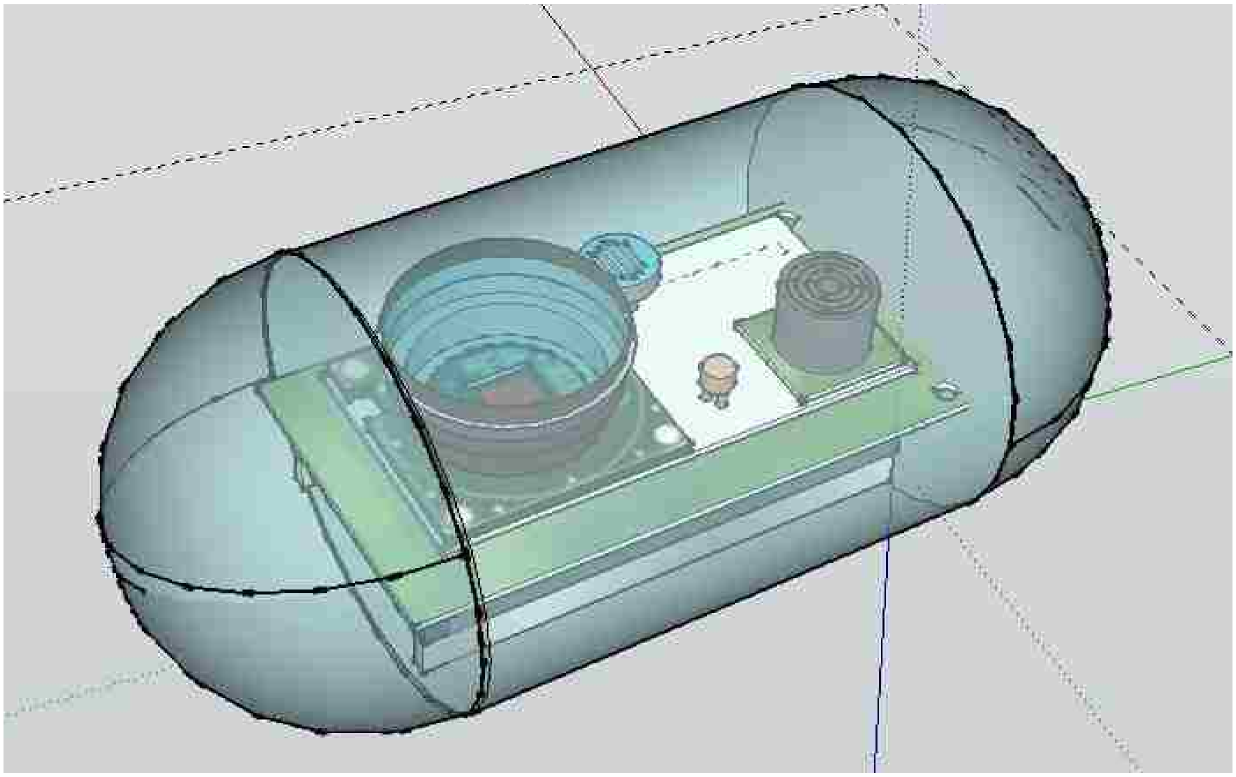
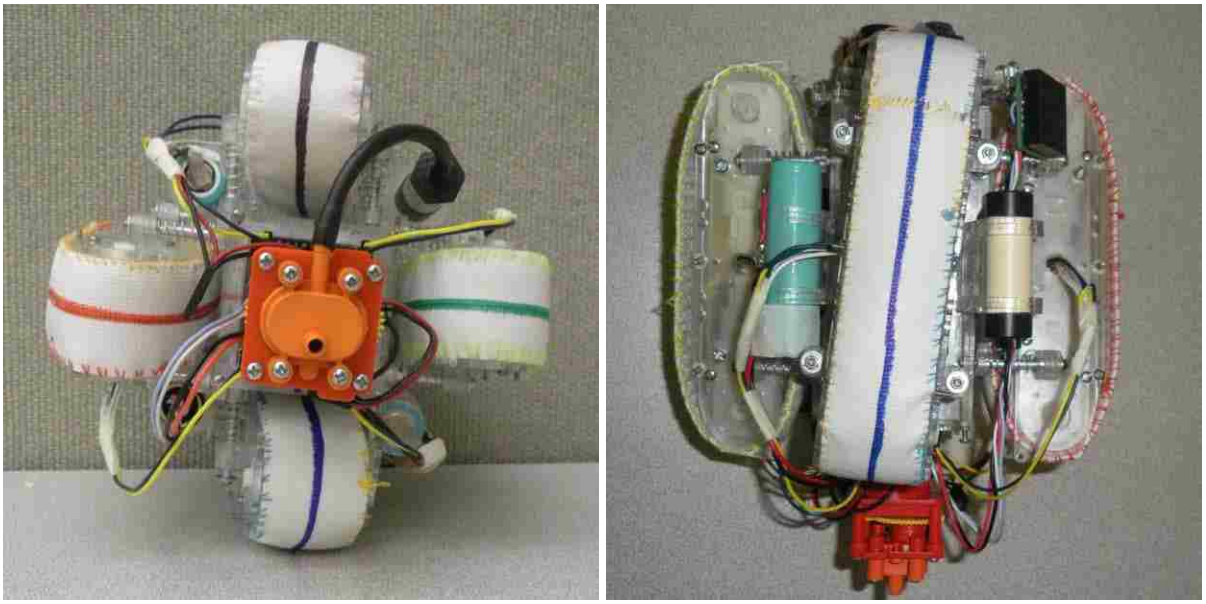


Figure 4.2: HPMS design

inspection and repair of the reported incidents, after the pre-processing realized by the HPMS inspection. This robot agent is an extended version of the agent we proposed in [34, 37]). It is capable of better mobility in complex topologies, copes with the presence of mass formation repair actions, and overcomes motion singularity problems imposed by direction changes and topology variation. It is also able to manage, monitor, and configure the other components within the pipeline. The robot agent is able to stop and even reverse motion in the pipeline for in-depth inspection of the detected incidents. A robotic arm is also associated with it which can be used to install markers within the pipeline, where manual installation is not feasible. It can perform physical actions to repair incidents.

The localization of a HPMS or a FAMPER within a marked pipeline (i.e. a pipeline where markers have been uniformly installed) is made by having these entities measuring the distance separating them from the closest marker upward the motion. Fig. 4.4 depicts an application of the SPRAM System.



(a) FAMPER: front view of tilted caterpillar (b) FAMPER: side view of tilted caterpillar

Figure 4.3: FAMPER design

In summary, the SPRAM system provides following four major functions:

- **Localization**: To achieve effective localization, the SPRAM System assumes that a scalable set of McRAIT systems is integrated inside the pipeline in such a way that they are uniformly distributed and the distance separating the McRAIT neighbors be controlled by the errors acceptable for an effective localization.

- **Inspection continuity management**: A McRAIT increases significantly the capacity of passive structures needed to store information collected by mobile sensors from pipeline inspection, authorize higher bandwidth for data communications with these structures, improve the event-related information collection and retrieval, and provides data loss-tolerance capabilities of the information collection system in the SPRAM System.

- **Event-related information management**: A McRAIT is used as a high capacity storage device to record history information provided by the active components of SPRAM System. The availability of this information is obviously needed for the continuity and efficiency of the inspection operation. It can, for example, help detecting a mobile sensor that got blocked

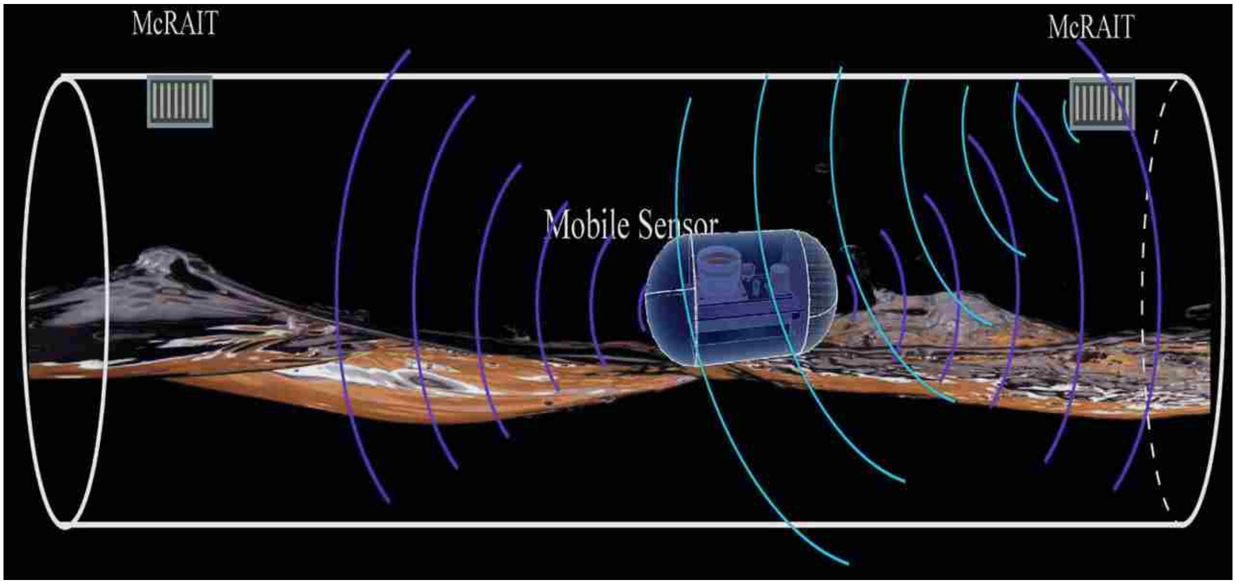


Figure 4.4: An application of the SPRAM system

by a scale formation. In addition, the history information built on a McRAIT system can be post-processed by the controlling system after an active component (e.g. mobile sensor) has copied them and delivered them to the controlling center.

- **Repairing**: The SPRAM System provides a fully autonomous topology-aware robot agent equipped with different kind of actuators for repairing pipeline damages depending on the inspection and repair demands. It is able to move properly and autonomously to repair the pipeline incidents after they have been identified and located.

4.2 McRAIT: Multiple Channel Redundant Array of Independent RFID Tag

In this section, we describe a new concept, called McRAIT. It is built to serve three objectives: First, it increases significantly the storage capacity available at each marker to provide useful information for sensors and robot agents to achieve pipeline monitoring through the RFID systems. Second, it allows higher bandwidth of data communication with the passive-based structures implemented at the markers. Third, it improves the fault-tolerance capabilities of the tags available at a given marker by providing redundant storage. The concept builds on the RAID technologies and adds ad hoc management of the data it may contain. It also builds on two other ideas provided in [8] and [45]; namely, the use of multiple tags and the use of multiple channels concurrently.

Bolotnyy and Robins[8] have studied methods to improve the RFID detection function by using multiple tags set up on an object, while ensuring data collision avoidance. They show that multiple tags can be deployed in a variety of applications and serve many useful purposes. In particular, multiple tags can be used for determining the identification and feature analysis of objects (such as product recognition in a warehouse and vehicle verification in a parking lot). They also support ensuring system reliability and availability, and even safety. In addition, the authors presume that multiple tags can be a considerable deterrent to illegal activities such as theft and forgery, and RFID privacy. The authors also discussed the fundamental issues of improving object detection by the use of multiple tagging. As multiple tags were used to provide redundancy without increasing the global storage and processing capacity of the systems allowed by the multiple tags, the developed system does not show a real benefit using the multi-structure, since it does not allow differential writing operations while maintaining tolerance.

On the other hand, Nakagawa *et al.* [45] has developed a multi-stage transmultiplexing digital down-converter for the implementation of RFID reader/writer on software defined radio capable of transmitting via 8 channels using 8 frequencies that are sampled at a single A/D converter and separated by digital down converters. The system developed allows 8 tags to concurrently send their data to a reader. This can increase the data gathering speed and can reduce data collision. However, the authors did not provide tolerance to the failure of tags and radio channels.

4.2.1 The McRAIT Architecture

Fig. 4.5 depicts the architecture of the McRAIT. Three major components are integrated in the McRAIT. They are: (a) the array of tags, allowing to integrate a reasonably large number of tags depending on the availability of frequencies it is using; (b) the low radio range multi-channel transponder, which is responsible for the physical communication with the array of tags; and (c) the McRAIT controller, which provides the basic functions to implement the logical mapping. Transponder and controller are implemented, in our application, at the robot and mobile sensor levels, while the arrays of tags are set up on markers placed at different locations on the pipeline. Marker placement on the pipeline can be done prior or during pipeline operation. In fact, the robot can be responsible for setting up the markers.

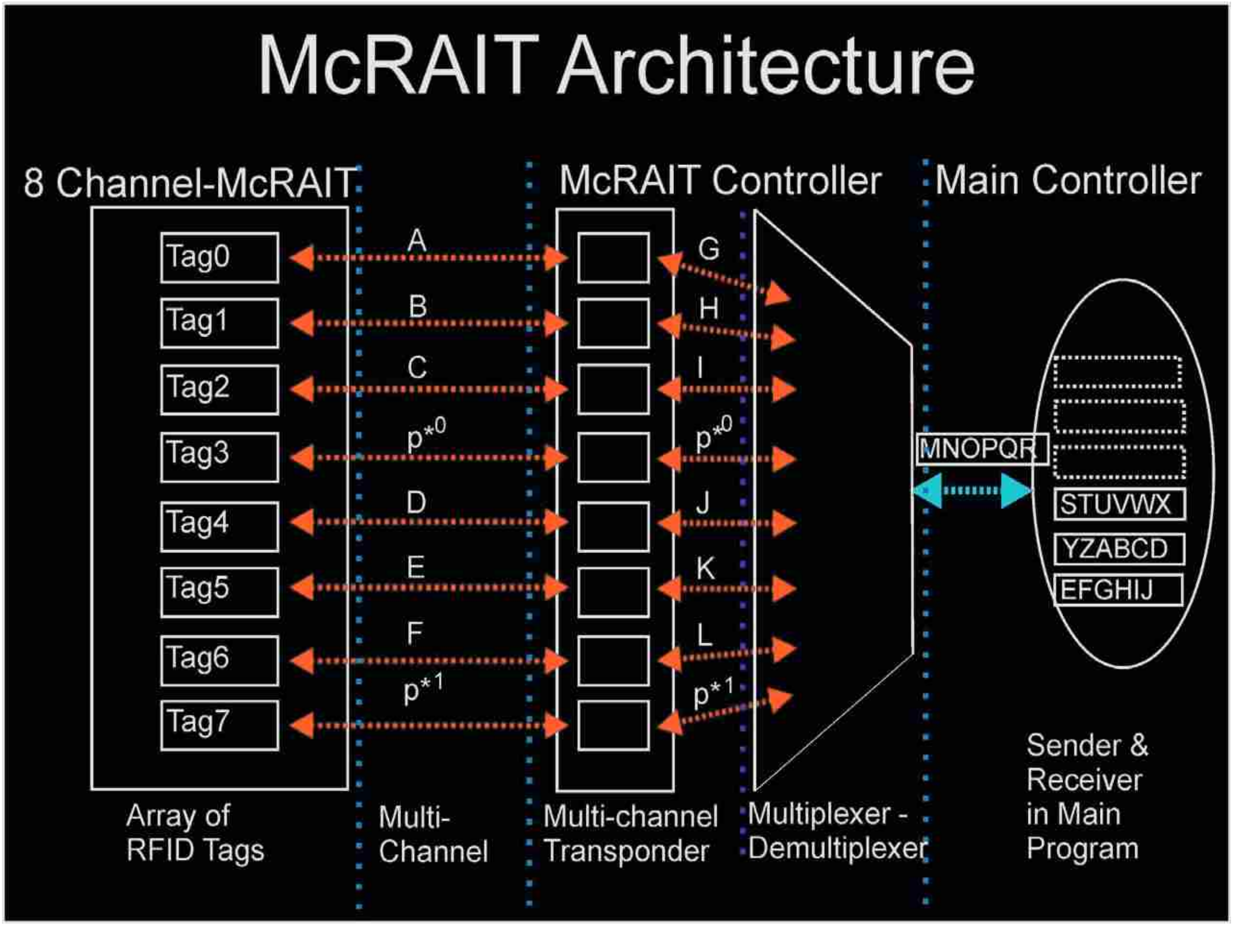


Figure 4.5: The McRAIT architecture

The McRAIT architecture provides fault-tolerance using multiple multi-channel RFID tags that adapts to the channel of each tag. It implements multi-channeled RFID readers/writers and a McRAIT controller. This system provides a mechanism to manage concurrently data on multi-tags by segmenting and storing it in a way similar to the storage of data in a system using Redundant Array of Independent Disks (RAID) [50]. In addition, it guarantees tolerance to the occurrence of tag and frequency failures. The data that need to be written on the tags is fragmented by the McRAIT controller, and then the data is sent to the specific tag via the multi-channeled RFID writers corresponding to its related channel. The fragmented data can be retrieved by the multi-channel readers associated with the channel of each tag and then merged by the McRAIT controller before the data is sent to the sender/receiver.

Considering failure addressed by the McRAIT, it is worth noticing that it can occur when a tag or the channel serving it is unavailable to send or receive data. To overcome such failure, the McRAIT is equipped with, like RAID 5 and 6 do, a mechanism that allows tolerance to a maximum of two failures. Indeed, it can be made tolerant to a higher number of failures.

4.2.2 Functions of the McRAIT Controller

A McRAIT controller has two major functions: multiplexing/demultiplexing and communication with markers and sender/receiver main program. Additional functions can also be embedded in the McRAIT controller for specific needs. Among the additional functions the McRAIT controller can have, one can mention authentication, data encryption, and special operation commands such as batch deletion. All functions included in the controller should be able to perform autonomously. Each read and write operation that is going to be performed in the RFID tags has to be atomic when executed by the controller so that it can provide, later, multiple physical storages as one logical mapping without requiring preprocessing for read/write operations to the sender/receiver main program. The McRAIT controller is also capable to report communication failure/s to the main program when it reissues the commands over certain number of times.

Multiplexing/Demultiplexing: Multiplexing is a read operation in the McRAIT controller executed on multiple tags. When data arrives from the tags in the array, in response to a request sent by the controller, this operation collects the data from each channel and merges it after data validation using redundant information coming along with the data. After multiplexing, the resulting data is transmitted to the sender/receiver main program. Demultiplexing is an atomic operation performed by the McRAIT controller. When a command (such as read, write, or delete) arrives from the sender/receiver main program, the controller decomposes it based on the rules dedicated for tag storage optimization and redundancy. Then it builds, for each tag, the related command issued from the original command and the demultiplexing operation.

The controller also provides an acknowledgment mechanism to check whether an operation has been multiplexed or demultiplexed successfully. The success of a command can be acknowledged by simply getting a response to a new read operation or getting a reflection of the execution on the McRAIT. When a demultiplexing operation succeeds, an acknowledgement is sent to the sender/receiver main program. Rules involved in building the commands related to tags attempt to assign to, every segment obtained after data decomposition, the tag that will store it such that whenever k channels or k tags fail to respond a command, coming from the controller, then the controller is able to reconstruct the whole command from the responses it gets from the other tags (typically, $k = 2$)

Communication: Frequency sharing reduces the potential for mutual interference between tags. It can also allow to increase storage capacity. To provide frequency sharing, the McRAIT assigns a single frequency to each tag. The array, as assumed to contain as much tags as the frequencies available, can be addressed by the controller for read and write operations the same way the system described in [45]. When a larger number of frequencies is required, several tags are assigned the same frequency. To deal with such situations, a frequency division multiplexing (FDM) is set up on the McRAIT to manage the use of a shared frequency between a group of tags.

The FDM defines a frame having n slots, where n is the number of tags in the group to which a frequency has been assigned statically. The slots within a frame are assigned to the tags of that group. Each slot is decomposed into two sub-slots. The first sub-slot is used to wake up the related tag in the group, and the second sub-slot is used to execute commands on that tag. In addition, the implementation of the FDM makes it feasible that during a slot only one tag is able to be operated, meaning that the controller is able to communicate with the tag to which the slot has been assigned and not with the other tags that are sharing the same frequency. Several additional operations can also be performed by the McRAIT controller. Among these operations, one can mention the following:

- **Authentication:** This function allows to authenticate the identity of a tag and to check the integrity of its content. It also can check whether a write command is authorized. To do so, a unique identity (UID) and a very light page table (VLPT) is set up for every tag. To achieve authentication, the controller should have a copy of every legitimate UID and should manage and sign the VLPT of each tag it operates on. A mutual authentication can be needed when some tags are not allowed to deliver their content to an unauthorized sender/receiver.

- **Data encryption:** The McRAIT controller can encrypt data and enhance its security with simple fragmentation and encryption operations. For example, the McRAIT controller can encrypt data before or even after data fragmentation. Moreover, it can encrypt each fragmented data or selected fragmented data. It is worth noticing that the tags are not involved in any active task related to encryption or decryption.

- **Special operation commands:** The McRAIT controller can invoke special operation commands such as batch commands. Those commands can also be sent on each channel for all tags and can be reissued when a failure occurs.

Due to the relatively slow communication speed with tags, several simple tasks, such as the batch deletion, which is involved in the aforementioned functions are implemented by the McRAIT on the tag-side. These tasks help the McRAIT controller in reducing transaction load. Nevertheless, the McRAIT can increase speed of communication, memory capacity, and tolerance by simply adding tags and using more frequencies.

4.2.3 The McRAIT Fault-tolerance

The RAID and the McRAIT system present several similarities. First, one can notice that both components use redundant and independent storage and parallel communication. Second, both of the architectures they set up increase capacity, read/write speed, and fault-tolerance. To support the latter feature, the McRAIT system implements extra hardware and software controller to operate.

On the other hand, some differences should be noticed. First, the McRAIT architecture is responsible for managing properly the limited energy it collects from the incoming communications. It also needs to manage optimally the processing memory. In particular, the McRAIT implements a VLPT entry and controls its size. It also supports all requirements for finding, updating, and deleting requested data to/from tags and allows delivering the UID and VLPT at the beginning of each transaction executed by the McRAIT controller on the array of tags.

We have selected two implementation strategies for the McRAIT architecture: McRAIT 5 and McRAIT 6. In particular, the read/write and data placement strategies (as used in RAID systems) have been adapted to the McRAIT architecture. Some other read/write strategies can also be adapted to the McRAIT architecture.

The McRAIT 5 (defined as striped tags with distributed or interleaved parity) strategy combines three or more tags in a way that protects data against the loss of any single tag. The storage capacity of the array is a function of the number of tags minus the space needed to store the needed parity. The parity information can be implemented using striped set with distributed parity or interleaved parity. Distributed parity requires all tags but one to be present to operate. In fact, when a tag failure occurs, the content of the array is not affected by this failure and the content of the failing tag can be restored. However, the system is unable to restore two-tag failures.

The McRAIT 6 (or striped tags with dual parity) strategy combines four or more tags in a way that protects data against loss of any pair of tags. The parity information can be implemented using striped set with dual distributed parity. It provides fault-tolerance from two-tag failures and guarantees the continuity of the array operation in the presence of two failed tags. This makes the McRAIT systems built on a group of 4 and more tags more practical, especially for the availability of data in pipeline systems. The experiments section, in the following, will analyze the relationship between the number of tags within the McRAIT and the performance of the pipeline monitoring.

When implementing the aforementioned strategies, fault-tolerance becomes increasingly important because large-capacity tags may add extra delays to the time needed to recover from a failure. In addition, single parity McRAIT strategies are more vulnerable to data loss and generate more delays when more than one tag failure occurs. Dual parity strategies give the opportunity to rebuild the array without data loss if two tags fail.

4.2.4 Design of a McRAIT System

A RFID system consists of two primary components - a tag and a reader. RFID tags, which are the wireless barcode labels applied to objects, are usually attached to a tracking object; a reader is then used to track tagged objects. At its simplest form, a tag is a beacon announcing its presence to a reader. When a RFID reader integrated with a mobile sensor transmits a signal, the RFID tag can charge up, when the received signal is strong enough, and it clocks out the data associated with it so that the reader sees the data it contains. In addition, a RFID tag has an antenna that emits radio signals to activate the tag and read/write data to it.

A tag can hold a unique identity (UID) that can be used for inventory management at the global scale. More than just holding an UID, a tag can carry re-writable persistent storage accessible via a reader. In this sense, RFID tags can extend a sensor network by providing sensing properties to otherwise un-sensible objects; thus, they provide the last-hop connection of a sensor network.

In the SPRAM System, the RFID tags work as fixed sensors. They are integrated under a McRAIT structure inside the pipeline at reasonable distance between each other, while RFID reader/writers are integrated in the mobile sensors and the robot agents. Sensors and robot can read and write the McRAIT tags that are available in their course of operation for recording the events. They also can collect the history of events stored on the McRAIT systems and clean their content, when needed. The RFID tags used in the SPRAM System are passive in the sense that they are powerless and make use of the incoming radio waves to power their response.

The SPRAM System uses arrays of eight tags (of the order of 2048 bytes) providing a storage capacity of the 12 KB ($= 6 \times 2KB$) for storing event information and 4 KB for fault-tolerance. The content of every tag is divided into three types of areas to allow the storage of data structures. The first area is is located at the front of the tag and contains only the data related to the identification of the tag and the table reporting on the page content (VLPT). 8 bytes are used for tag identification, which allows the management of 4 billions tags, if only half of them is used and the other half is reserved. The VLPT contains 4 rows of 16 bits each. The bit located at the i-th row and the j-th column shows whether the j-th 32-bit word in the i-th block is empty (bit equal to 0) or full (bit equal to 1).

The second area includes the information related to the history of sensor mobility. Every data structure related to history is assumed to start with a 0-bit and can be appropriately structured. The third area contains the information related to the events detected by the sensors. Every data structure related to events starts with a 1-bit.

Every data structure reporting on history or incident events is a 32-bit word. History data structure contains information about the sensor ID associated with history event and the timestamp of the storage operation. Incident event data structure contains information about the timestamp of the storage, event location, event type, and some extra information related to the event. The structure used for the event location field contains a pair (r, n), where r is the effective distance to the closest tag to the event occurrence and n is the number of tags separating this tag to the tag storing the incident event data structure. Therefore the distance separating the incident position and the marker containing the related event is bounded by 2^s, where s is the number of bits used to store n.

Memory management in the RFID tags is handled using the following different situations:

- **Managing memory full condition:** If the memory entries of the McRAIT located at a marker in the vicinity of a mobile sensor are full, then the data reported by the sensor is stored in the next McRAIT tag that is able to contain it, provided that the distance to the available tag can be reported in the event location field. When no tag is available within the next 2^{s-1} markers, then the mobile sensor has to randomly select a McRAIT among the following 2^{s-1} markers, delete its oldest entry and store the reported event.

- **Initializing the monitoring:** When the process of inspecting the pipeline starts, the first mobile sensor to be inserted in the system will be in charge of reading the content of the markers it encounters and deleting all entries they contain in the history and event related area by putting the 0-bit to the VLPT, and storing its identity in the history area. The deletion operation can be subject to some criteria, when needed. In particular, when there is a need to keep the information related to a preceding inspection, the deletion will be performed using conditions on the timestamp field.

- **Entry duplication:** To cope with the limited space in the McRAIT systems located at different markers, redundancy is reduced to a minimum. To this end, storing an event at a given time is subject to the absence of report on this event made by another mobile sensor prior to it. This assumes, however, that the sensors need to be synchronized. Synchronization can be easily performed at the entrance of the pipeline.

- **Tracking mobile sensors:** To provide tracking capabilities and sensor blocking, every mobile sensor is required to register its identity, along with a timestamp, on the markers they come close to. However, a selection criterion can be applied during registration to reduce the effect of this operation on the storage capacity. In particular, registration can be operated on only selected markers, based on any density-aware selection criteria (for example, the registration can be made every 5 McRAITs).

4.3 HPMS: High Performance Mobile Sensor

4.3.1 Design of a HPMS

The SPRAM System requires high performance processing power for the mobile sensors in order to achieve accurate inspection and execute the complex functions, which may be integrated. Since the mobile sensor's mission within the pipeline does not last long time, the power limitation does not affect such achievement. Notice that power limitation is a serious handicap for sensor-based applications such as those using MICA [16]. Indeed, MICA-based applications integrate very slow processing units (e.g., Atmel ATmega 128L processors running at 4MHz) and are not capable of high computing tasks, since they are built to operate for long periods of time without being able to be recharged .

In order to fulfill its requirements, the HPMS is designed with four components: a main board, a McRAIT controller, a sensing platform (containing different sensors), and a container. It has a flexible interface to integrate other sensors and communication capabilities. It also needs to be sufficiently small size and light to facilitate its transportation by the liquid inside the pipeline.

The main process in the HPMS manages complex tasks and controls the sensors and the McRAIT controller. It consists of two components: an Overo-board [17] and an interface board (Fig. 4.6). The Overo-board is made by Gumstix Inc. It has 600MHz OMAP 3530 Applications Processor with ARM Cortex-A8 CPU, 256MB main memory, and 256MB flash memory. It provides Wi-Fi and Bluetooth communication capabilities. Moreover, it is equipped with the C64x+ digital signal processor, which accelerates processing of signals coming from sensors. It also provides the POWERVR SGX for 2D and 3D graphics acceleration. All these functions are completely implemented in a very tiny board of size 17mm x 58mm x 4.2mm.

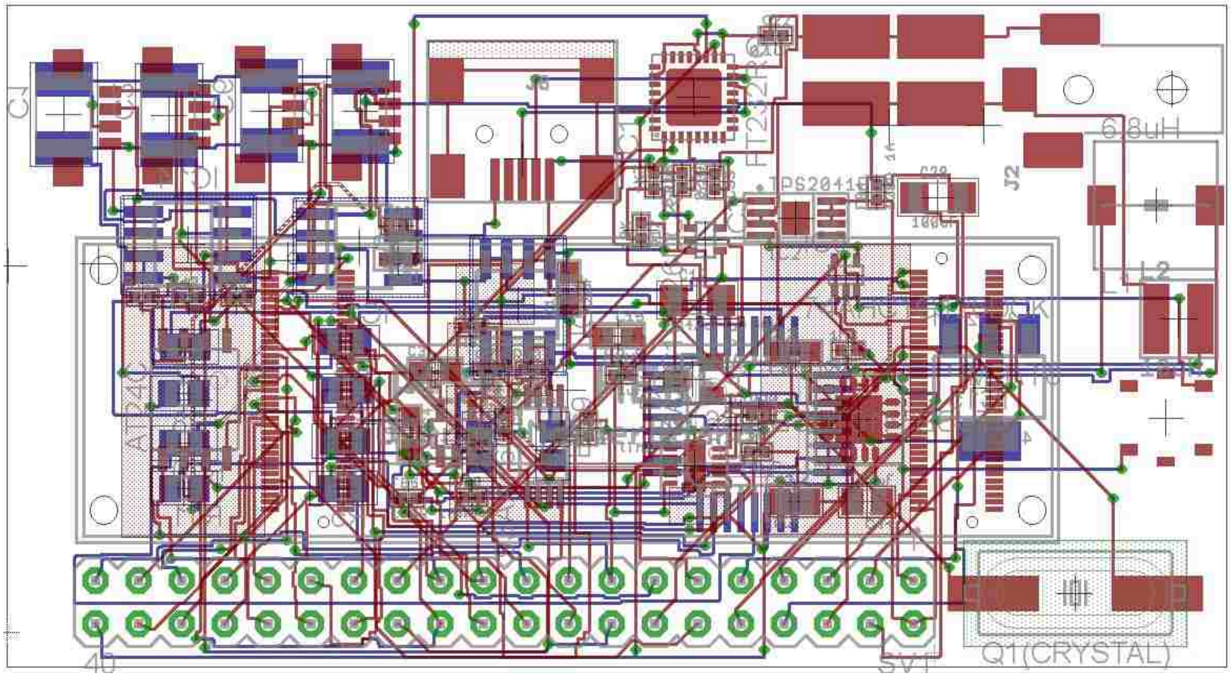


Figure 4.6: High Performance Mobile Sensor (HPMS) interface board

The interface board is designed to integrate various sensors such as CCD camera, ultra sonic sensor, and chemical sensors. It is made fully connected to the Overo-board through two 70-pin AVX 5602 series connectors. Moreover, the interface board provides 4 generic USB ports and regulates stable electric power from batteries to supply all devices in the HPMS. Extra sensors can be added to the HPMS through USB ports, or through extension boards stacked on top of the interface board.

The McRAIT controller integrates the SkyeModule M10 UHF module [63] and a redundant array of independent tags (RAIT) software. The SkyeModule M10 performs power control and noise reduction. It provides a library, called SkyeAPI, that simplifies and automates the RFID tag and protocol-specific functions. The RAIT software provides McRAIT 6 read/write strategies. It allows the main program to handle multiple tags as a unique logical storage volume. In addition, it implements the function in charge of distance-to-marker computation and environment recognition.

Lastly, two types of containers are used within the HPMS to protect the whole device from external hazards and provide floating capabilities. The two types are the capsule container and the spherical container. The overall dimension of a container does not exceed 80mm, making the HPMS usable in small size pipelines. However, it can have larger size for more intensive functions, when used in larger sized pipelines.

4.4 FAMPER: Fully Autonomous Mobile Pipeline Exploration Robot

4.4.1 Characteristics

This particular design of the fully autonomous mobile pipeline exploration robot focuses on verification of the mobility mechanism in complex pipeline layouts consisting of different pipeline bends, and vertical and horizontal geo-spatial conditions with manual controlling system using Gumstix-based devices. The robot is implemented as a straight caterpillar-based wall-press robot for the efficient navigation and inspection of $\Phi130\sim150$mm pipelines. The robot consists of a main body, caterpillar wheel parts, four extendable link systems, and other attached functions as demonstrated in Fig. 4.7. The attached functions are composed of different sensing, communication, and actuation devices as per the pipeline inspection demands. The length of the robot is 148mm and the exterior diameter is 127mm at maximum shrinking condition and 157mm at normal condition.

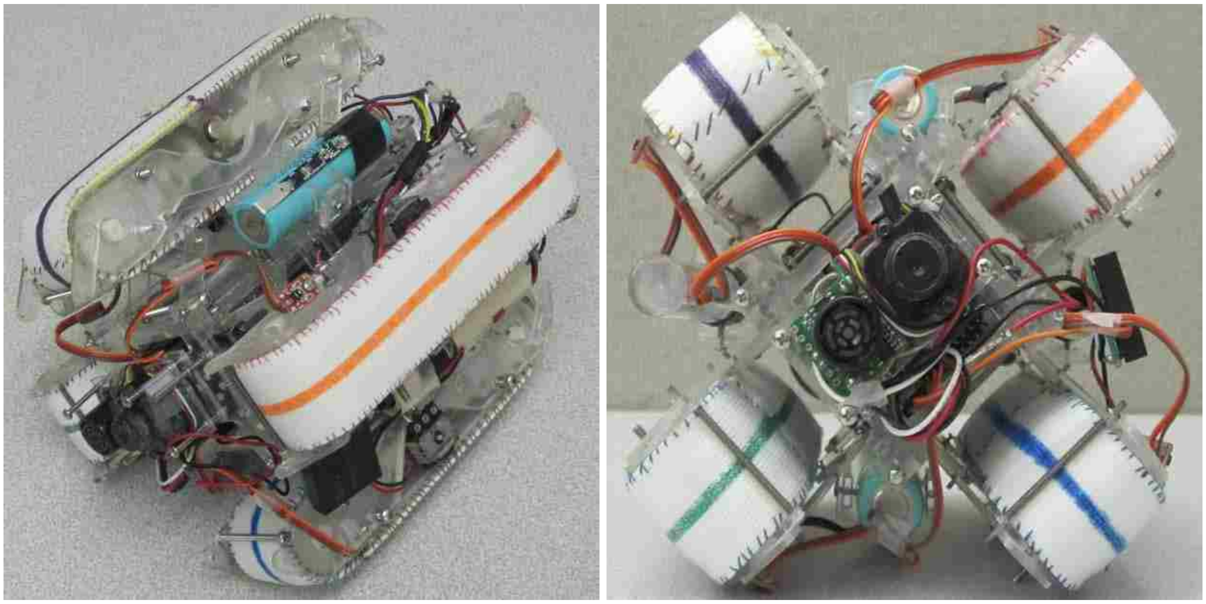


Figure 4.7: The autonomous pipeline exploration robot

The main body consists of a Gumstix board extended by some expansion boards with the required communication, sensing, and reaction capabilities and a extendable link structure which connects the main body to the caterpillar wheels. The interface board provides interface to the micro-controller, compass, 3D-accelerometer, rotary encoder, and Li-ion battery used in the robot. The body is constructed as a square shape, which is adequate to support the four extendable link systems and the size of the central body frame is 40mm×40mm×108mm. The caterpillar wheel is made of two motors attached one on each side of the wheel, a rotary encoder, and a wrapping belt. Each caterpillar wheel is arranged 90 degrees apart and each of which are 33mm wide and 148mm long. Below we present the summary of the robot characteristics and focus primarily on its motion planning mechanism, the detailed description of its characteristics can be found elsewhere [34, 37, 36].

- **Caterpillar mechanism.** The distance between the central body of the robot and the caterpillar wheels can be determined based on the movement of the flexible links, the elastic restoration force on the spring at each suspension link, and reaction forces from the wall. Each of the four caterpillars is able to hold the surface of the pipeline firmly while moving inside the pipeline very smoothly. The steering capability to go through 45 degree elbows, 90 degree elbows, T-branches, and Y-branches is provided by controlling the speed of each caterpillar independently through differentiating the speeds of the four caterpillars. The rotary encoder equipped in each caterpillar wheel calculates the distance moved so far and a set of two geared motors, two pulleys, and a belt transmits the driving power to the caterpillar. Moreover, the wall-pressing mechanism is developed to make the robot climb up and down in vertical situations. To achieve efficient wall-pressing mechanism, each caterpillar wheel is mounted to the central body using four independent suspension links. These links are responsible for giving the required gripping force to the robot and the robot can be contracted from 157mm to 127mm using these links. The suspension link's ability to contract and expand make the robot flexible enough to move through the highly-bent pipelines.

- **Operational architecture.** The operational architecture of the robot is given in Fig. 4.8 which consists of three operator modules: (a) Supreme Operator (SO); (b) Perception Operator (PO); and (c) Action Operator (AO). Each operator has different manager modules which perform fundamental operations with their own property values. The property values are stored in a central repository which can be referred and updated by the module which is accessing them and/or any other operator/s based on some predetermined rules. This modular ability of the architecture enables each module to be developed and extended independently. These property values can be changed by SO or PO depending on the environmental conditions or any other operator which might require to do so to perform its action. The central repository also contains the predefined rules, sensed data, map information, results of actions, and history of events of each operators. SO sends the decision message to AO to perform necessary actions. SO might also tune the property values of AO to make the action being performed by AO adaptable to the environment with time based on the indirect real-time feedback from PO. These messages can be feedbacked indirectly and receiver's

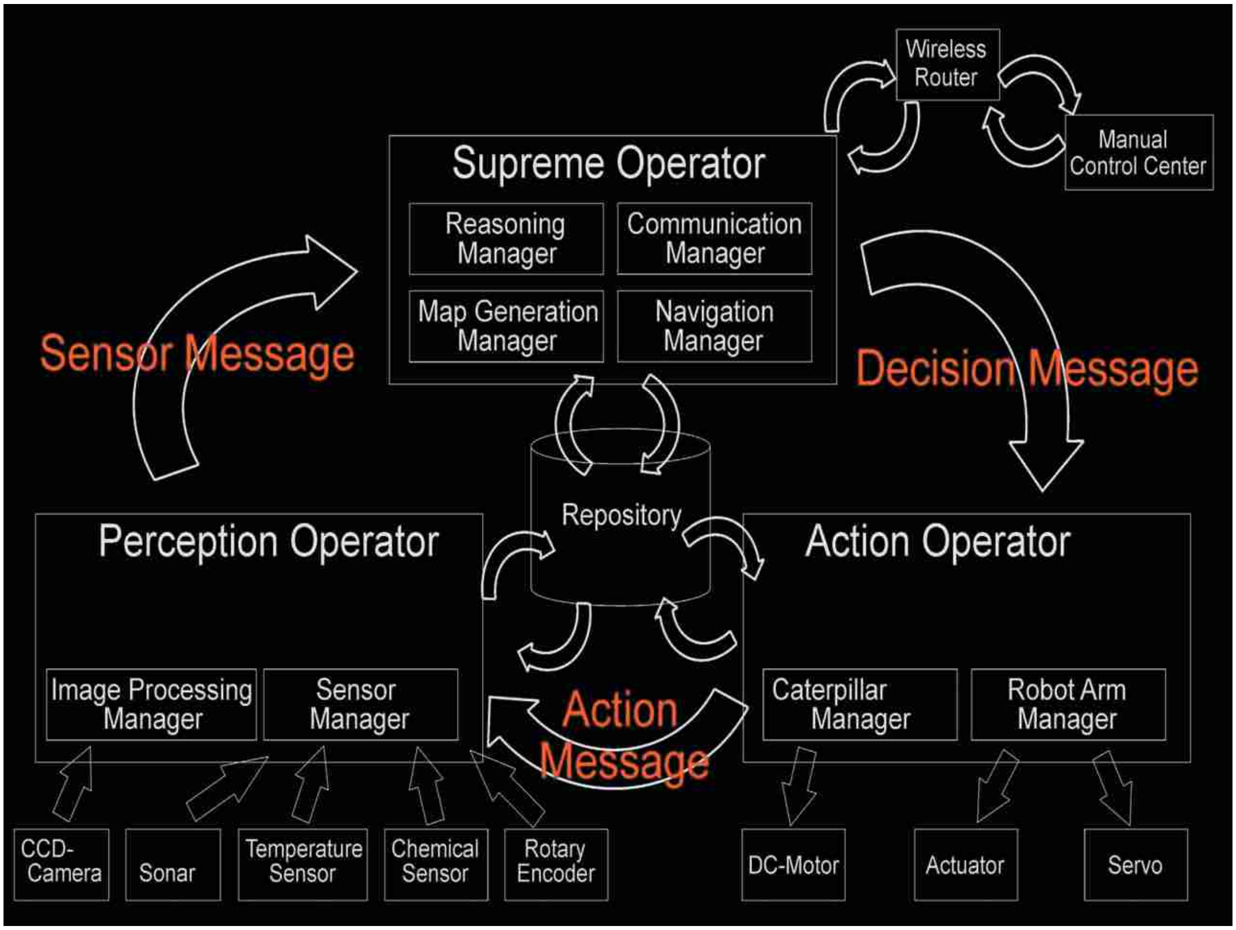


Figure 4.8: Operational architecture of the robot

property values can be tuned by the sender using those feedbacks.

- **Control architecture.** The control architecture of the robot as depicted in Fig. 4.9 illustrates motor speeds for all four caterpillars depending on the direction in which the robot is intended to turn. For example, if the robot wants to move forward in a straight pipeline, all wheels rotate in same direction with equal speed but when if it wants to turn 90 degrees, CM sets the motor speed of wheel 1 to 0 and motor speed of wheels 2, 3, and 4 to 10 based on the property values provided in Fig. 4.9. The robot can also monitor the wheel slipping in certain pipeline conditions and adjust the motor speeds based on the feedback generated by PO to cope with such situations.

- **Electrical architecture.** The electrical architecture of the robot given in Fig. 6.2 consists

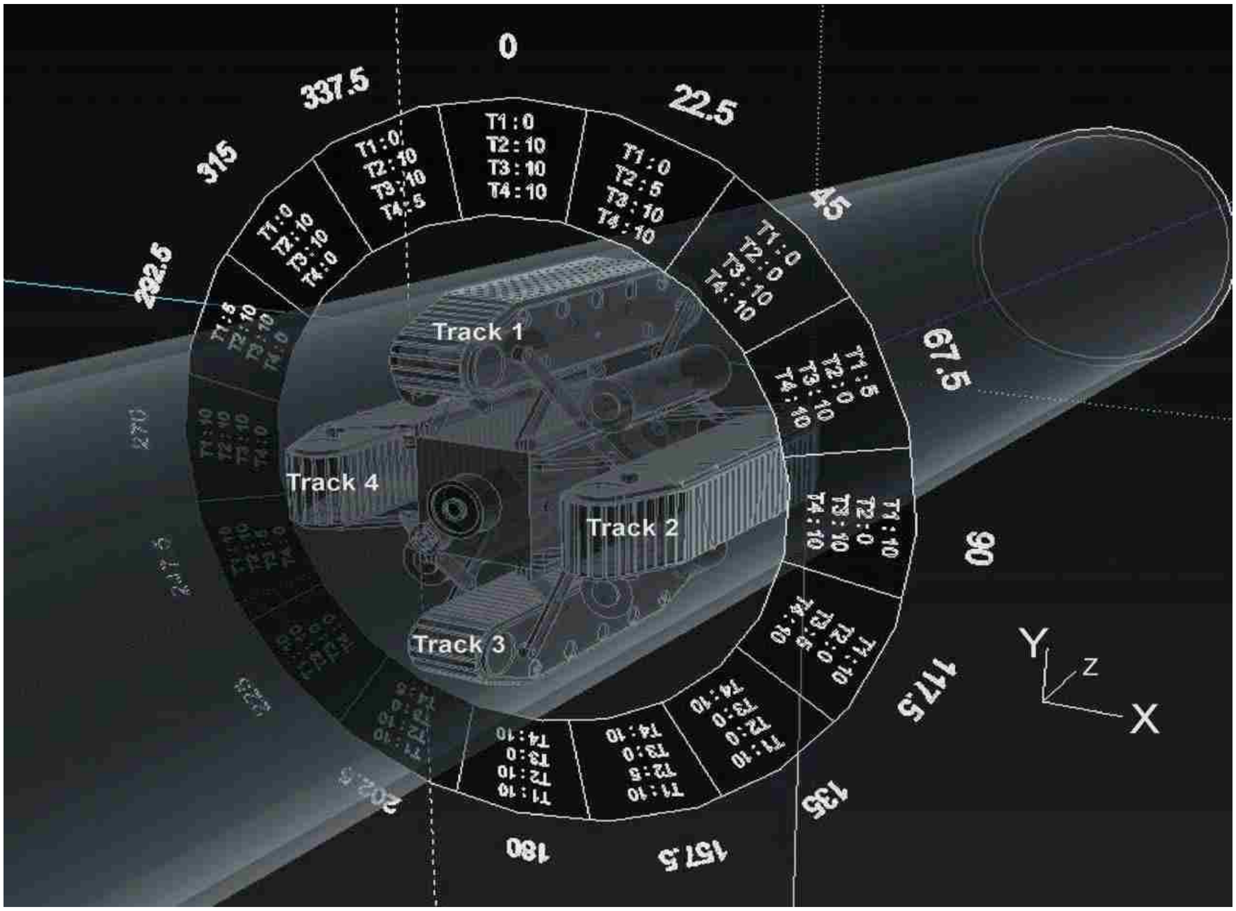


Figure 4.9: Control architecture of the robot

of four main components: (a) Interface Board (IB); (b) Expansion Board (EB); (c) Gumstix Main Board (GMB); and (d) Sensors and Controllers. IB is used to provide efficient and easy connection to all the sensors and some of the controllers; when one or more sensors are damaged then they can be replaced without disassembling the entire robot. It can also be used to connect all the expansion modules on to their respective interface boards. IB also regulates voltages of all devices and removes noises from DC motors. As Gumstix does not have in-built modules needed for communication, we integrated some expansion boards with the required communication, sensing, and reaction capabilities; some of which used in the robot are WIFI-Stix and Robostix.

Different sensing and controlling functions are also implemented in the robot to make it fully autonomous and mobile in pipeline inspection and exploration. A compass is integrated for

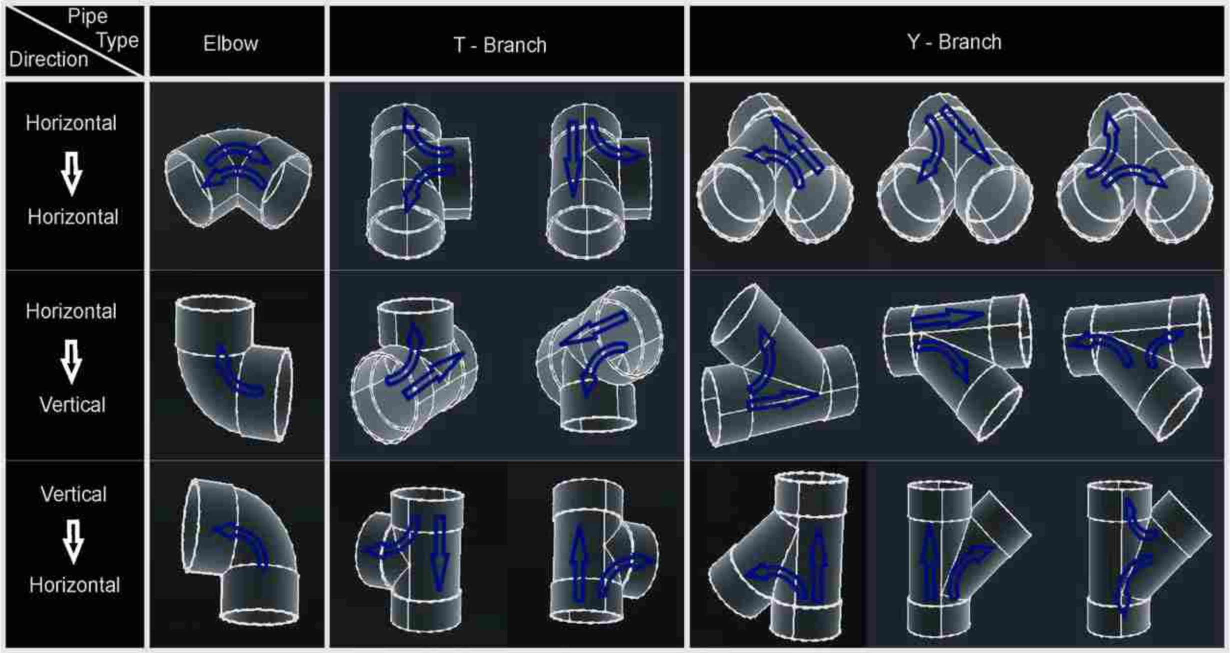


Figure 4.10: Different types of motion in elbow, T-, and Y-branches

obtaining the direction in which the robot is heading, a 3D accelerometer is used to get its tilt information, and a sonar is used to determine the obstacle or hole position in the pipeline.

4.4.2 Motion Planning of the Robot

We performed several experiments to check motion capability of the robot at 45 and 90 degrees elbows, T-, and Y-branches. At 45 and 90 degrees elbow, there are 3 types, at T-branch, there are 16 types, and at Y-branch, there are 24 types of motion. Different types of robot motion in different pipeline bends (45 and 90 degrees elbows, T-, and Y-branches) are given in Fig. 4.10.

4.4.2.1 Motion Planning

- **Motion planning at 45 degrees elbow.** The motion planning of the robot at 45 degrees elbow is similar to the motion planning of 90 degrees elbow given below.
- **Motion planning at 90 degrees elbow.** The motion planning of the robot at 90 degree elbow is given in Fig. 4.11. The robot make a turn by making stationary the wheels contacting the

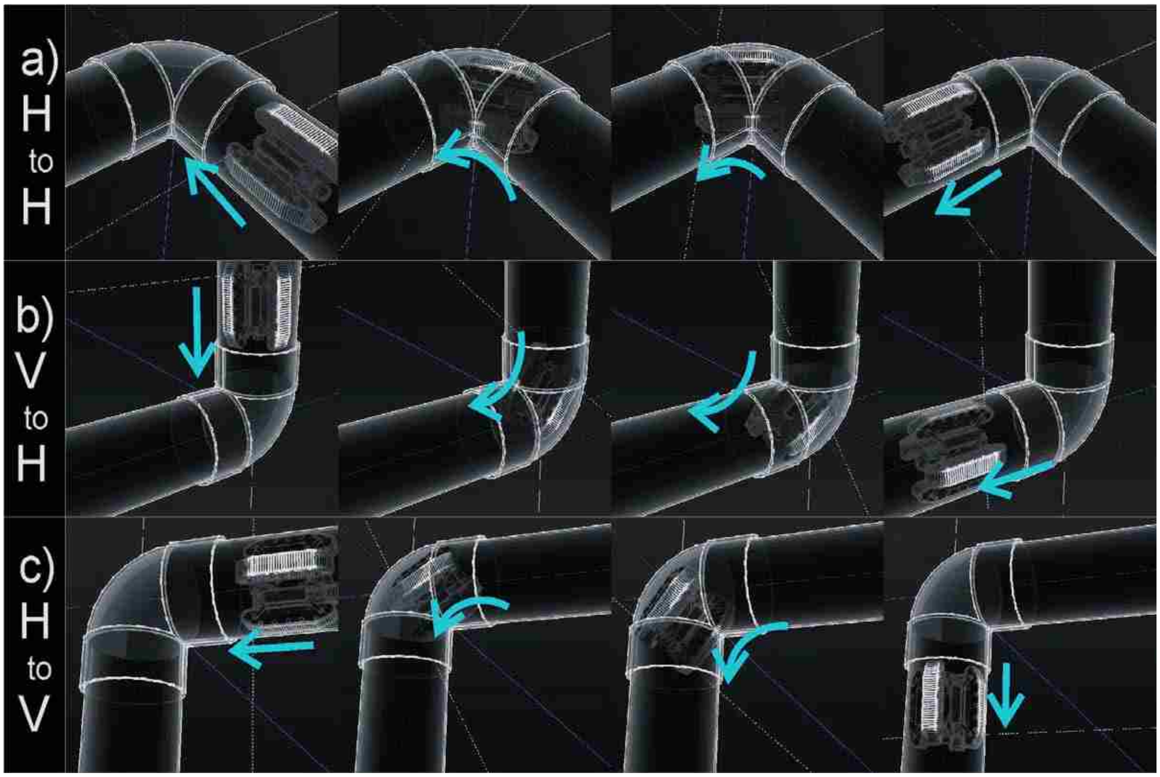


Figure 4.11: Motion planning at 90 degrees elbow, where H to H indicates Horizontal to Horizontal, V to H indicates Vertical to Horizontal, and H to V indicates Horizontal to Vertical motion

inner corner of the 90 degrees elbow and rotating the wheels contacting the outer side of the 90 degrees elbow toward vertical or horizontal direction it intends to turn.

- **Motion planning at T-branch.** The motion planning of the robot at T-branch is given in Fig. 4.12. It has been observed that motion planning at T-branch is more complicated since there are many paths at T-branch. From our experiments, the transition from the horizontal to the vertical motion inside the pipeline is found to be the most difficult scenario. This is due to the small area of contact for the caterpillar wheels to be able to make contact to the inside wall of the pipeline. When there is a very small area of contact, the robot wheels cannot apply the functionality of differentiating the caterpillar's speed for making a turn. The depiction of the pipeline surface contact by the caterpillar wheels at T-branch for the successful motion is given in Fig. 4.13, where the circled parts denote the contact areas. In the scenarios depicted in the figure, the robot can make a turn by making stationary the

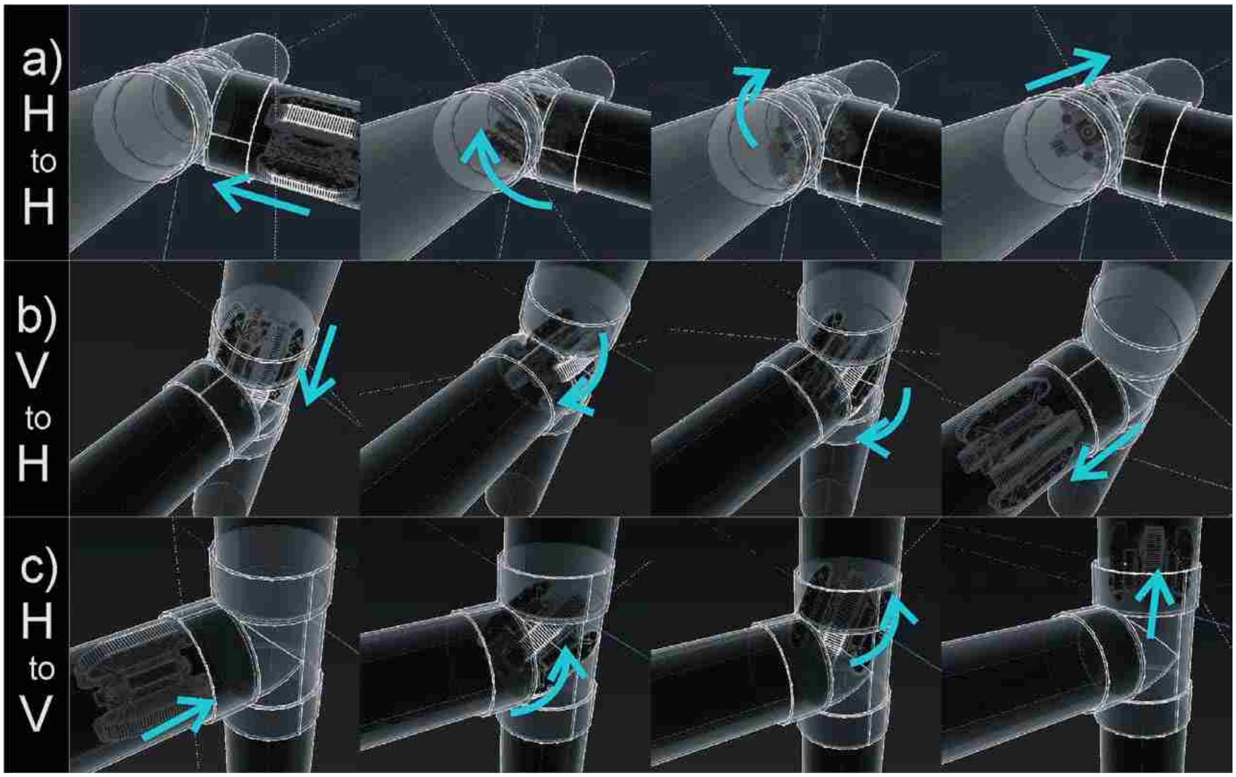


Figure 4.12: Motion planning at T-branch

wheels contacting the inner corner of the T-branch and rotating the wheels contacting the outer corner of the T-branch toward the vertical side. The control architecture of the robot described in Fig. 4.9 provides the functionality of controlling the motor speeds to achieve such scenarios.

- **Motion planning at Y-branch.** The motion planning of the robot at Y-branch is given in Fig. 4.14. The motion planning in Y-branch is relatively easy in comparison to T-branch, so we skip the discussion here.

4.4.3 Design of a FAMPER

The robot agent we have designed for the SPRAM System is a fully autonomous robot, in the sense that: (a) it carries all required modules for accessing any pipeline region; (b) it runs a control program for navigation and incident analysis; and (c) it reacts to incidents using on-board resources. The robot agent has four caterpillars set up uniformly all around the robot body.

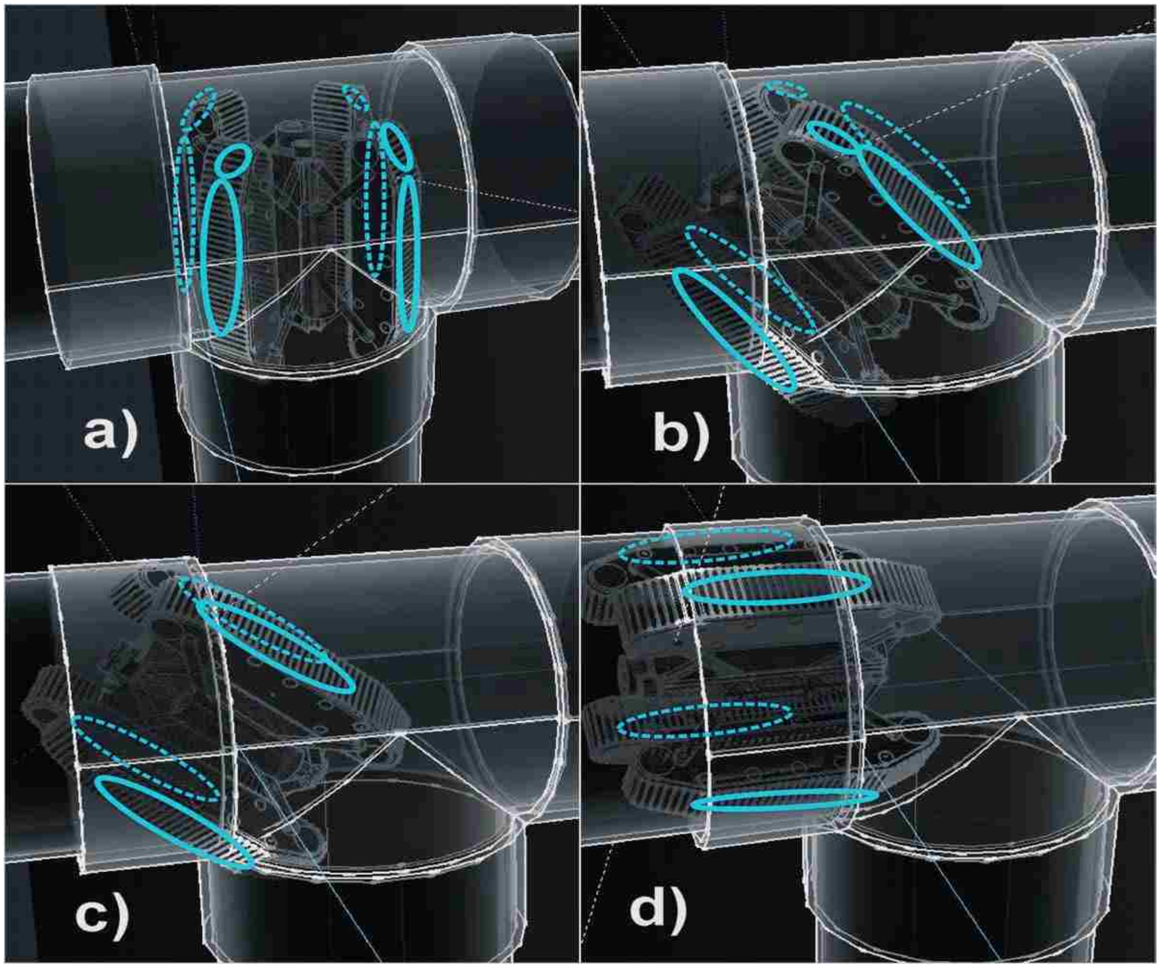


Figure 4.13: Depiction of the pipeline surface contact by robot wheels at T-branch

Two types of caterpillar control mechanisms can be used. The first is able to attach the caterpillars to the robot in a tilted way in order to provide a spiral motion of the robot inside the pipeline (5 degrees tilted caterpillars have been prototyped as depicted in Fig. 4.3). We have found that the spiral motion performs better than the straight-forward motion in the presence of motion singularity problems [39]. In particular, the tilted caterpillars provide the functionality to self-adjust the position so that three or more caterpillars eventually get in contact to the surface of the pipeline wall, on the occurrence of motion singularity conditions.

The second mechanism is built to allow caterpillars to be bendable and segmented into three frames: the front, the middle, and the end frames (as depicted in Fig. 4.15). The front and end frames are linked to the middle frame using an initial 30-degree bending. They can be bendable by

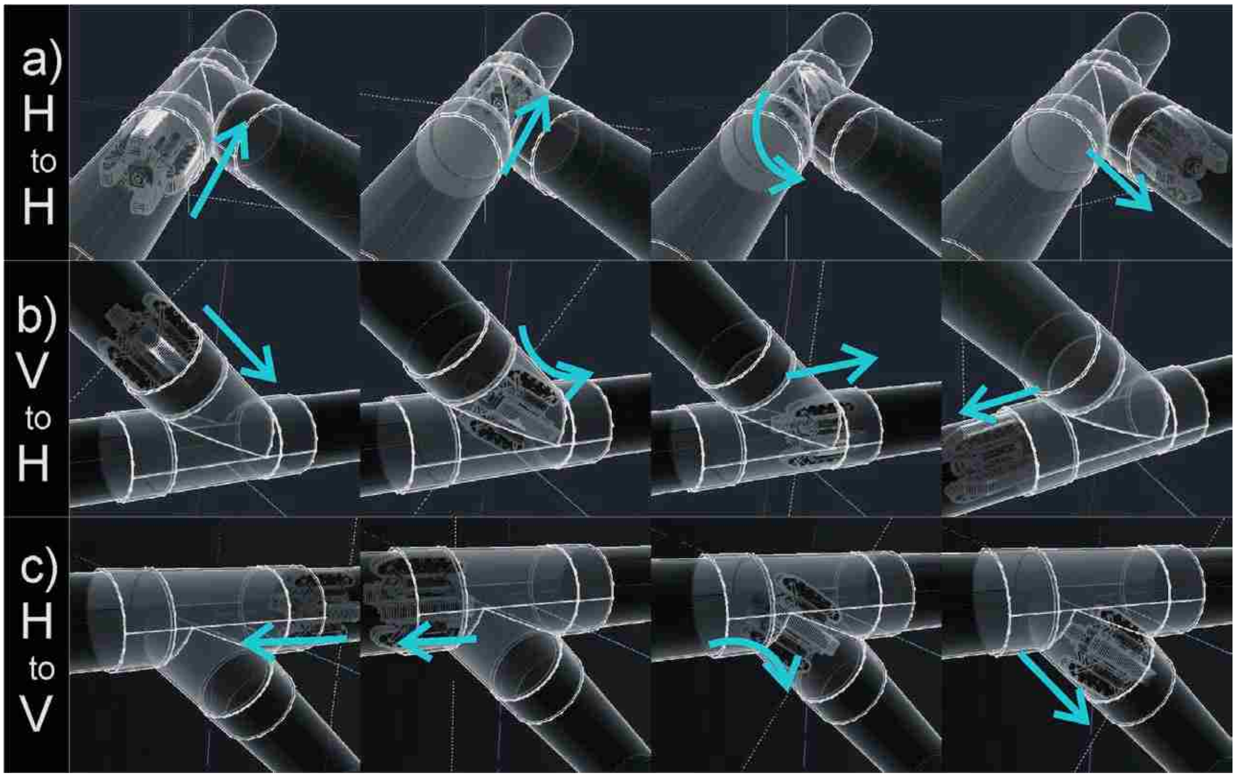


Figure 4.14: Motion planning at Y-branch

a maximum of 60 degrees, thanks to a 30-degree extra bending. The segments aim at enhancing flexibility of the robot in crossing obstacles and changing directions in different pipeline bends. The middle frame has four shrinkable shafts that provide support and 50% shrinkability for the caterpillar frame, giving the robot the flexibility to use in inspecting pipelines of variable sizes. In particular, the robot agent we have designed in the Robotic Research Laboratory (LSU, Louisiana) allows a total frame length of 40mm and a maximum shrinkability of about 20mm, as shown in Fig. 4.16, where the outside circle represents the pipeline wall and the dotted circle shows the size at full shrinking condition.

The design based on segmented caterpillars can provide a good capability of the robot to travel vertically as well as horizontally in pipelines with different fittings. It has also addressed two other challenges: the electrical and reactivity challenges. To address the electrical challenge, we made the electrical part of the robot water-proof including sensing activity, processing power, and memory management. To address the reactivity challenge, the design of the robot has included space

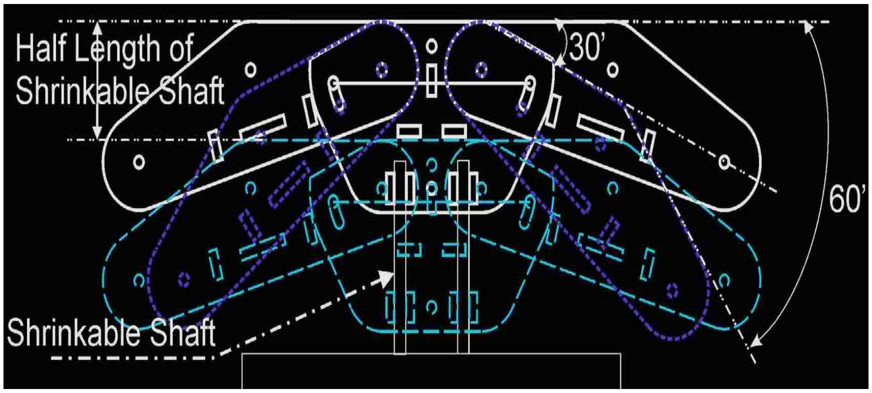


Figure 4.15: Side view of the stretchable caterpillar

and processing resources for two types of reactive actions to incidents: chemical and mechanical actions. For chemical actions, the robot is equipped with a chemical sprayer, while it integrates a robotic arm to react on physical incidents.

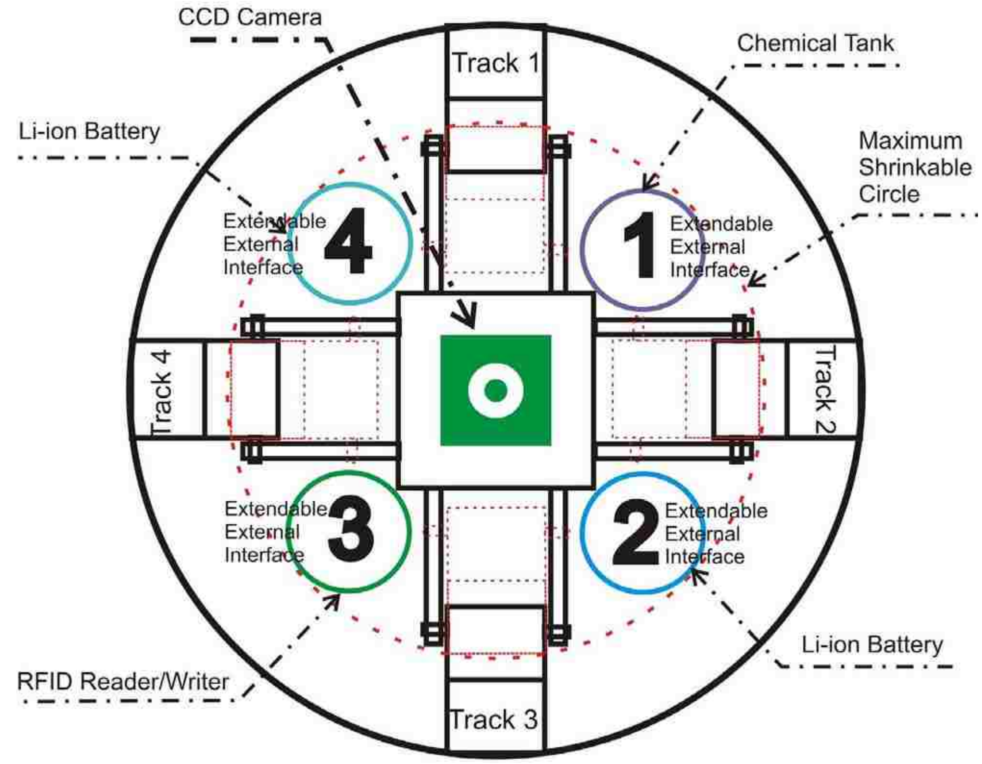


Figure 4.16: Sectional view of the robot agent

Chapter 5

A Technique for Incident and Sensor Localization

In this chapter, we gives a technique for incident and sensor localization. First, we describe maximum range estimation between RFID tag and reader, then we provide the McRAIT-based location technique.

5.1 Maximum Range Estimation

Let us assume that a transmitting RFID reader radiates in all directions with the same power density, that is the RFID reader is *isotropic*. We can picture the radiated power P_{reader} as being uniformly distributed over a spherical surface at any given distance r from the reader antenna. In this case, the power received by an RFID tag, P_{tag}, is:

$$P_{tag} = P_{reader} \frac{A_{e,tag}}{4\pi r^2}, \tag{5.1}$$

where $A_{e,tag}$ is the *effective aperture* of the tag antenna. It is not trivial to derive a complete expression for the effective aperture, since it depends on several parameters including the frequency of radiation and the environment where it takes place. However, it is convincing to guess that the effective aperture of an antenna around a half-wavelength long might correspond to a square around a half-wavelength on a side [14, 5]. For an isotropic tag antenna transmitting in a free space, $A_{e,tag}$ is approximately given by $A_{e,tag} = \frac{\lambda^2}{4\pi}$, where λ is the related wavelength.

While considering the tag antenna as a receiver, we can suppose that the antenna collects energy from some effective aperture. In fact, the size of the receiving aperture of any antenna is directly proportional to the gain of the antenna when used as a transmitter. This is a consequence of the *principle of reciprocity* [5, 48], which for our purposes, can be stated as: transmitting from antenna A and receiving with antenna B ought to give the same result as transmitting from antenna B and receiving with antenna A. Since we have the effective aperture for an isotropic antenna transmitting in a free space, we can write:

$$A_{e,tag} = G_{tag}\frac{\lambda^2}{4\pi}, \tag{5.2}$$

for *directional antenna* where the gain G_{tag} is measured relatively to an isotropic antenna or to a dipole antenna. Using this relationship, we can write a very general equation for the power received from a transmitting antenna $reader$ by a receiving antenna tag based on the gains of the $reader$ and the tag, assuming that the distance between them is known:

$$\begin{aligned} P_{tag} &= P_{reader}G_{reader}\frac{A_{e,tag}}{4\pi r^2} \\ &= P_{reader}G_{reader}G_{tag}\frac{\lambda^2/4\pi}{4\pi r^2} \\ &= P_{reader}G_{reader}G_{tag}\left(\frac{\lambda}{4\pi r}\right)^2. \end{aligned} \tag{5.3}$$

Eq. 5.3 defines a very convenient way to state the expected received power between a transmitter $reader$ and a receiver tag. Another important factor to take into account is the polarization for simple linear antennas by projecting the incident electric field onto the polarization axis of the antenna [5]. For the case of linear polarization, we just need to multiply the right term of the Friis equation by the *cosine* of the angle between the transmitted polarization and the receiving antenna axis, say θ_{pol}, to get the effect of polarization on the induced voltage. In this case, the Friis equation becomes

$$P_{tag} = P_{reader} G_{reader} G_{tag} cos^2(\theta_{pol}) \left(\frac{\lambda}{4\pi r} \right)^2 \tag{5.4}$$

and thus the *maximum forward-link-limited range* (denoted as $D_{forward}$ in our case) will be found to be proportional to the cosine of the misalignment angle.

From Eq. 5.3, defining the minimum power required by a tag to wake up and decode the reader signal as $P_{min,tag}$, we obtain $D_{forward}$ for a RFID reader as given below with the assumption that there is no misalignment in polarization:

$$D_{forward} = \left(\frac{\lambda}{4\pi} \right) \sqrt{\frac{P_{reader} G_{reader} G_{tag}}{P_{min,tag}}}, \tag{5.5}$$

and defining the minimum signal power for demodulation at the reader as $P_{min,reader}$, we obtain the *reverse-link-limited range* $D_{reverse}$ as:

$$D_{reverse} = \left(\frac{\lambda}{4\pi} \right) \sqrt[4]{\frac{P_{reader} T_b G_{reader}^2 G_{tag}^2}{P_{min,reader}}}, \tag{5.6}$$

where T_b (generally $= 1/3$ or -5dB [14]) is the backscatter transmission loss of the tag antenna.

To reach the maximum range provided by Eq. 5.5 and Eq. 5.6, we should have

$$\left(\frac{P_{reader} G_{reader} G_{tag}}{P_{min,tag}} \right)^2 \geq \frac{P_{reader} T_b G_{reader}^2 G_{tag}^2}{P_{min,reader}}, \tag{5.7}$$

which is equivalent to

$$P_{min,reader} \leq \frac{T_b}{P_{reader}} \times P_{min,tag}^2. \tag{5.8}$$

Therefore, the $P_{min,reader}$ should be smaller than $\frac{T_b}{P_{reader}} \times P_{min,tag}^2$ to allow proper communication at the distance equal to $D_{reverse}$. In the simulation, the latter value is referred to the maximum distance.

5.2 The McRAIT-based Localization

We first discuss the scenario we consider to localize a sensor node that goes through the pipeline, detects an incident and reports it to the closest marker. Fig. 5.1 illustrates this scenario.

1. When the sensor detects an incident (or wants to report on its position), it identifies the type of environment it has to transmit in using an ad hoc sensing function.
2. The sensor transmits a signal with a power P_{reader} which reaches the nearest tag T_1 and the the next tag T_2, with a power fulfilling the conditions established in the previous subsection.
3. The signal received by the tags is reflected back to the source sensor. It computes the distance r and r' to tag T_1 and T_2, using the appropriate formula given by Eq. 5.5.
4. The sensor selects the nearest tag if the error on the location is smaller than a given threshold. Otherwise, it selects the second nearest tag. Then, it stores in the selected tag the computed distance as the localizing distance.

The computed distance locates the sensor position (and the incident event, if any) as if it were flowing close to the pipeline wall (this assumption is at the origin of the error addressed at the end of this section).

In order to perform these steps, we suppose that the distance made by the sensor node during the signal round-trip can be approximated to zero. Consequently, the angle α between r and r' is too small and both the transmitted and the reflected signals make nearly the same distance. In the following, we formally establish the expression of this distance.

Let r be the distance separating the sensor node from the nearest tag. According to Eq. 5.4 and Eq. 5.6, r can be expressed as follows:

$$r = \left(\frac{\lambda \cdot cos(\theta_{pol})}{4\pi}\right)\sqrt[4]{\frac{P_{reader}T_b G^2_{reader} G^2_{tag}}{P'_{reader}}}, \tag{5.9}$$

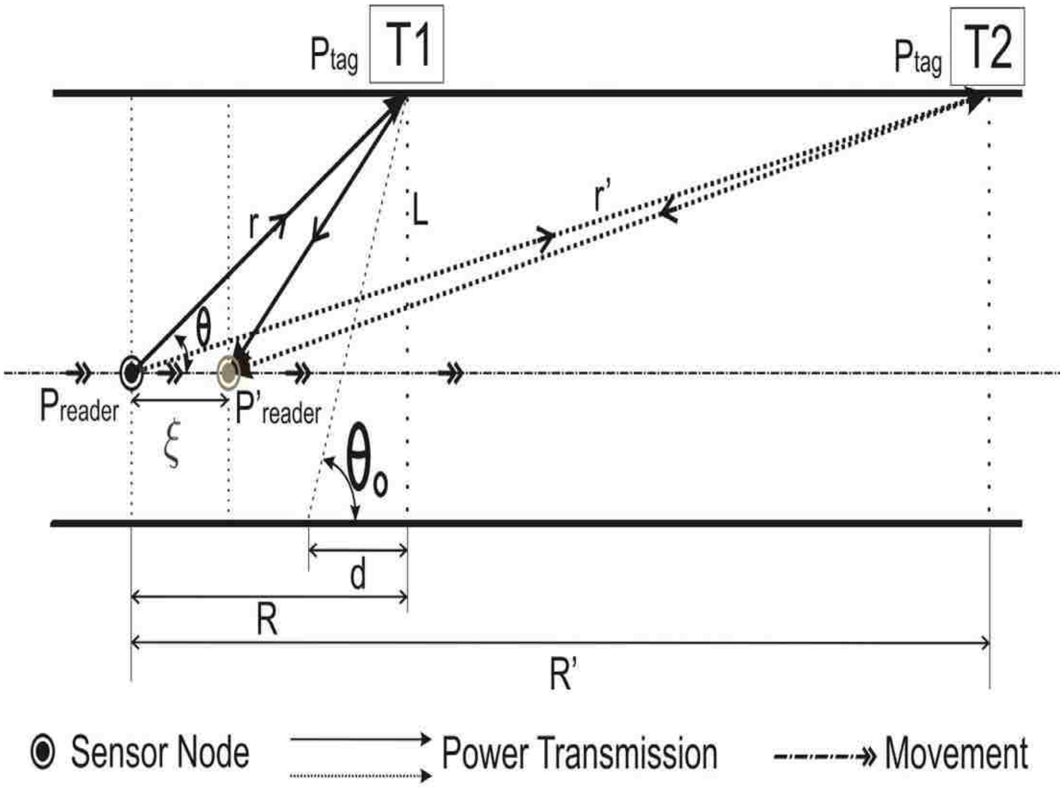


Figure 5.1: Sensor localization within the pipeline.

where P'_{reader} is the received power at the system. The relative error associated to the computation of this distance should fulfill the following inequality:

$$\frac{\Delta r}{r} \leq \frac{\Delta P_{reader}}{P_{reader}} + \frac{\Delta P'_{reader}}{P'_{reader}} + \frac{\Delta \theta_{pol}}{\theta_{pol}} + \frac{\Delta T_b}{T_b}, \tag{5.10}$$

where $\frac{\Delta X}{X}$ denotes the relative error associated with a measurable variable X.

Assuming this, it comes that, if the system is able to provide P_{reader}, P'_{reader} and θ_{pol} with less than 3% error, then the error made on r would be no more than 10%. Thus, the efficiency of the distance computation may be controlled by the errors made on P'_{reader} and θ_{pol}.

Supposing that the processing delay at the tag level is minimal with respect to the propagation delay, the distance ξ made by the sensor node during the signal round-trip is given by Eq. 5.11.

$$\xi = \frac{2.r.V_m}{V_p}, \tag{5.11}$$

where V_m is the sensor velocity and V_p is the propagation delay related to the liquid injected in the pipeline. This means that $\frac{\xi}{r} = \frac{2.V_m}{V_p}$.

Let us now estimate the error Δr on the distance r reported by a sensor to locate itself or an incident it detects with respect to a selected Marker. Let R be the actual distance, then the error Δr is given by

$$\Delta r = r - R \leq r(1 - cos\theta). \tag{5.12}$$

Therefore, the relative error $\frac{\Delta r}{r}$ is smaller than $1 - cos\theta$. Then, allowing a sensor that is separated from tag T_1 by a distance d smaller than $\frac{L}{tan\theta}$ to communicate with the next tag T_1 would guarantee a relative error smaller than $(1 - cos\theta)$. In particular, if a threshold is set for $1 - cos\theta$ to be equal to 10%, for example (i.e., $\theta = 25$ degrees), then the above assumption gives a value for d smaller than $d = 2.1 \times L$, where L is the diameter of the pipeline. For $\theta_0 = 15$ degrees, the relative error is smaller than 4% and d is smaller than $3.7 \times L$.

We will study in the Chapter 7 the variation of the error experienced by the measure of the distance between a sensor and a selected tag to which the distance is computed.

Chapter 6

Prototyping of the System

A prototype for the SPRAM System is currently under development to provide a thorough analysis of all functions and features. A first version of the prototype including several components have already been completed. It integrates: (a) a storage device having the capability to store information about health-related events and sensor location capable of reducing marker's failure; (b) a robot agent capable of spiral and vertical motion in 150mm pipelines; and (c) a reader and writer system capable of supporting incident location. Ongoing activities are now considering the implementation of: (a) a configurable McRAIT system that copes with large applications and provides tolerance to tag and channel failures; (b) a prototype for the HPMS including various sensor functions and efficient power management including sleep-mode strategies that allow the coordination of HPMS activities, in order to cope with long pipelines; and (c) different robot agents adapted for different pipeline usages and sizes.

In particular, several strategies to increase the HPMS inspection range can be achieved by adjusting the quality of inspection, controlling communication with McRAIT-based markers, and using multi-HPMS-coordination. Nonetheless, we have found that, in the case of sewer pipeline (with a fluid speed of about 0.5 km/h), the maximum inspection range of HPMS that can be easily achieved is 4 km. Therefore, an accurate coordination between 25 HPMSs allows an inspection range higher than 100 km.

Moreover, HPMSs can be configured with different strategies to increase their lifecycles. Two kind of strategies can be applied to this end, the *collaboration-in-group* strategy and the *individual-target-range* strategy. In the former strategy, a bunch of HPMSs acts as a collaborating group and allows only one HPMS, in the group, to be active at a time. An efficient communication scheme coordinates the sleep/awake process of the members of the group. In the latter strategy, the HPMSs are configured with different target range settings on which they switch to active mode while they will be in sleep mode the rest of the time.

The prototype for the robot agent (depicted in Fig. 4.3) has 4 expandable one-segment tilted caterpillars, which allow horizontal and vertical mobility and changing directions. It commands differentiated and controllable speeds for the caterpillars. The robot has attached an RFID reader/writer to collect information stored at the tag level, a chemical tank and sprayer for actuation purposes, two Li-ion batteries for one hour life, and a CCD camera for creating high-quality, low-noise images related to inspection. The robot prototype is designed to have high processing power, large memories, and several sensing functions. In addition, the robot has four extendable external interfaces to add different modules for pipeline inspection demands as shown in Fig. 4.16.

6.1 Prototype of the Robot Agent

- **Hardware platform.** The components of the robot are given in Fig. 6.1. A small but powerful computing system based on Gumstix main board is assisted by two interface boards: Robostix and WiFi-stix. They are interconnected to all the internal ports of the Gumstix, Robostix, and WiFi-stix, and also with the attached sensors and external controllers. They also regulate the power for all the internal boards. This layout gives easy and universal access to all the ports available in front and rear part of the central body system.

  The robot has attached RF-CCD Camera, which can send the video stream independently, and the sensors such as a 3D-accelerometer, a compass, and a rotary encoder for particular purposes. Robostix provides the required pins to read data from available sensors by for-

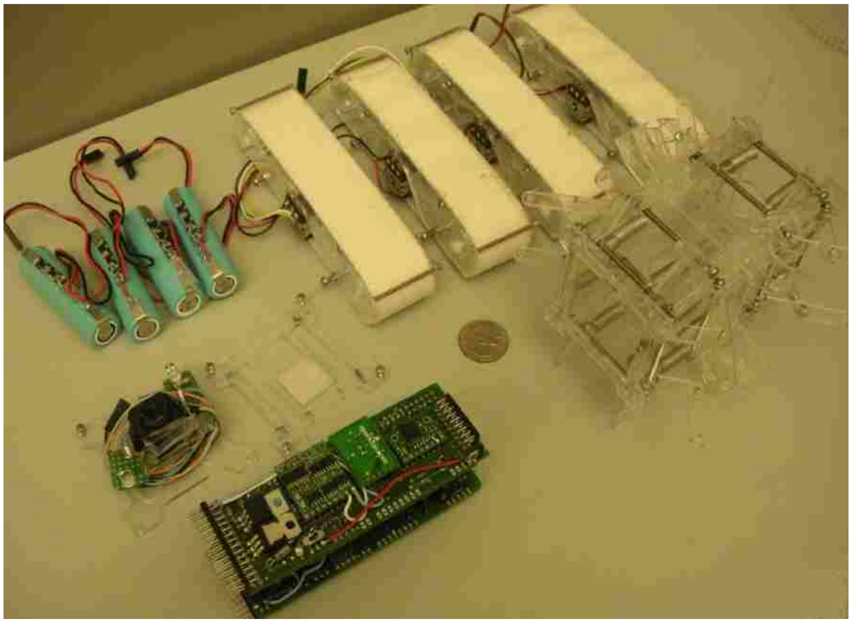


Figure 6.1: Components of the robot

warding them to the Gumstix after converting them from analog to digital. WIFI-Stix adds the functionality of transmitting and receiving data to and from a remote computer using wireless network. Gumstix is installed with embedded Linux platform which has the capability of running programs written on high level languages. In this implementation, we programmed the controlling interface using Java. The sensor readings have been read using programs written in AVR-C which are later ported to the Robostix.

- **User control interface.** A Manual Control Program (MCP) has been developed to operate the robot in different pipeline layouts. The program comprises of four major panels: (a) 3D view of the robot's position; (b) RF video panel to display video stream from RF camera; (c) Control Panel (CP) to control the robot using the the robot Controller (FC) and/or the GUI interface and to provide the tilting and direction of the robot as indicated in mini 3D view; and (d) Message Console (MC) to display the detailed status of the robot. The controlling signals are sent to the computer running the MCP using FC as given in Fig. 6.3. FC uses an analog joystick and also provides flexibility of sending the control signals using Bluetooth and USB connections. In order to control the robot from a remote location, we used RF video

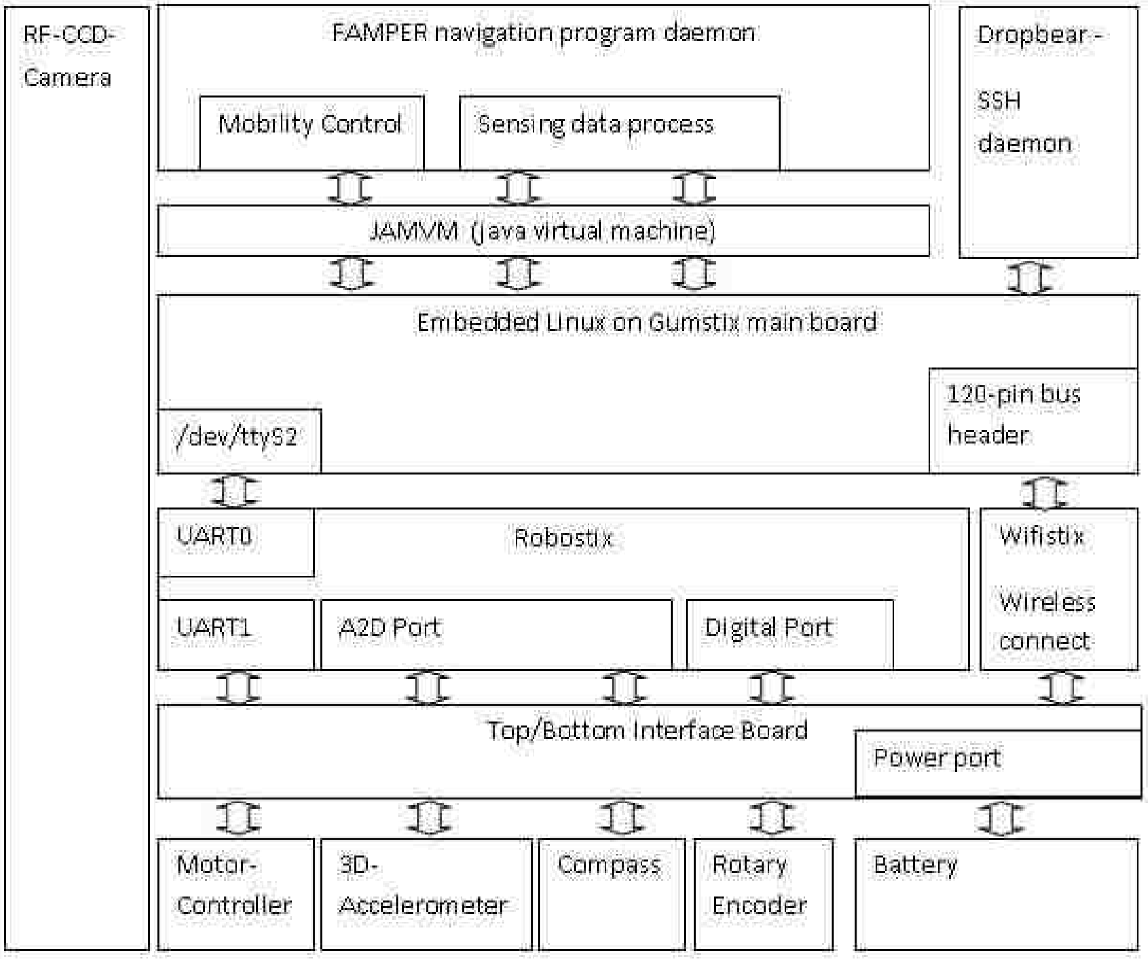
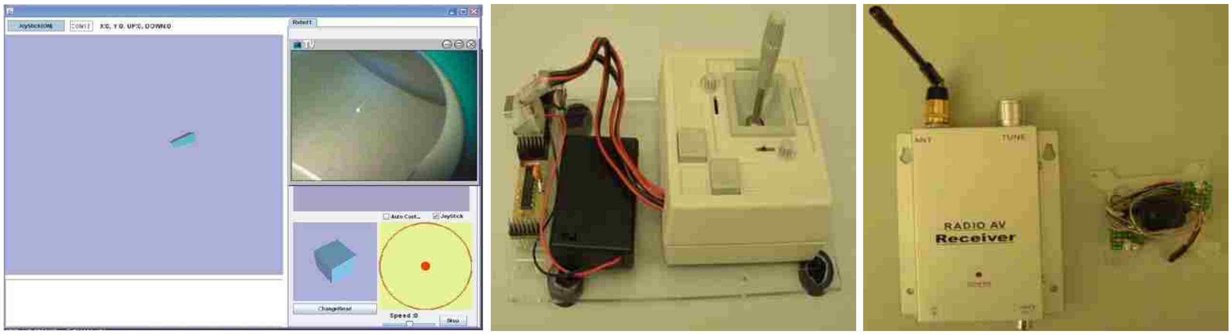


Figure 6.2: Electrical architecture of the robot

system which is small in size, consumes low power, and have high sensitivity in inspecting the situations inside the pipeline. We have also added ultra bright LEDs which help the RF video camera system to capture the robot environment.



(a) Manual control program (b) FC controller (c) RF video system

Figure 6.3: Controlling and RF video system

Chapter 7

Experimental Results

This chapter gives experimental result of SPRAM System. First we provide performance evaluation results of a robot agent, then we show experimental results of the SPRAM System on various experimental environments.

7.1 Performance Evaluation of the Robot Agent

7.1.1 Experimental Testbed

The experimental pipeline layout is given in Fig. 7.1. It is constructed including all possible pipeline bends and contains one 45 degrees elbow, one 90 degrees elbow, one T-branch, and one Y-branch. The inside diameter of the sewer pipeline used in the experimental pipeline layout is 150mm. First, the robot is evaluated in different pipeline bends separately. Later, the robot will be evaluated in a complex pipeline layout of Fig. 7.1.

For the experimental evaluation, the robot is employed in the inspection of a complex pipeline layout, that has been constructed using all available pipeline fittings that a typical pipeline system uses, where the robot also needs to perform vertical and horizontal motion. Recall that one of such complex pipeline layout used in the experiments is given in Fig. 7.1. The robot is first experimented in each bends individually and then experimented to the whole pipeline layout. The robot manages

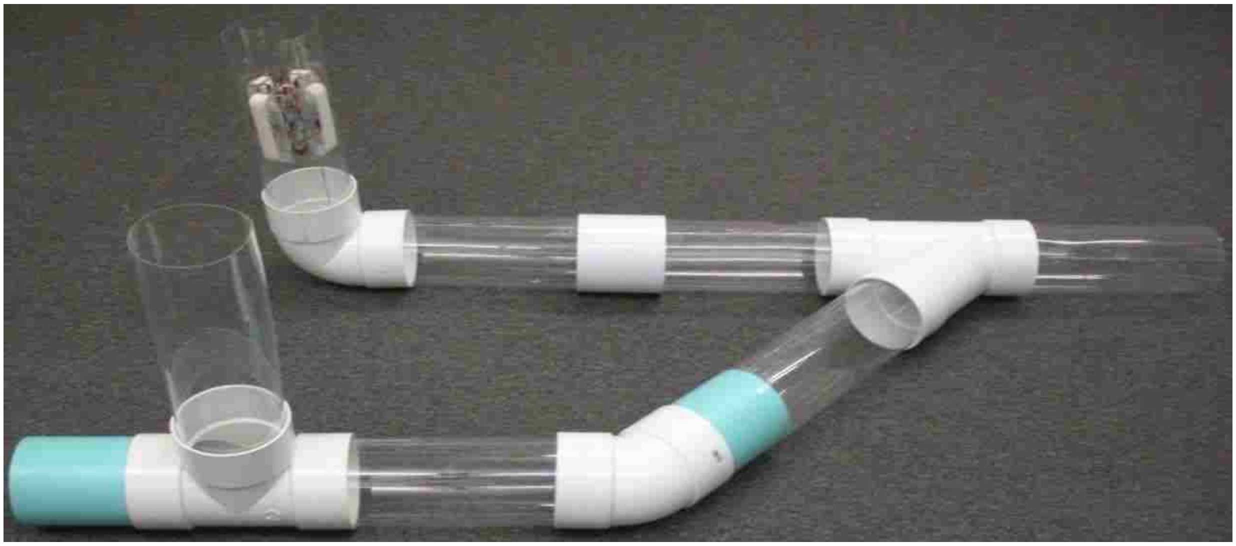


Figure 7.1: Experimental pipeline layout

to travel through the layout by changing the motor speed appropriately. The Fig. 7.2 shows that the pipeline exploration robot is traveling to several directions (including climbing up and down in the vertical pipeline) in the 90 degrees elbow of the experimental pipeline layout (types of motion at 45 degrees elbow is similar). The Fig.7.3 shows that the robot traveling to several directions in a T-branch of the experimental pipeline layout. Similarly, the Fig. 7.4 shows that the robot traveling to several directions in a Y-branch of the layout. The video clip available here [2] shows the performance result of the robot in the whole pipeline layout.

7.1.2 Performance Analysis of the Robot Agent

- **Analysis of singular motion.** In this section we discussion the motion singularity conditions we observed in the experiments. The motion singularity problem [39] has been observed for some of the cases while the robot was passing through T-branches because the robot looses contacts at turning position as shown in Fig. 7.5. This is because the two caterpillar wheels are not able to contact the surface of the pipeline (the × denotes the no contact points which are indeed need to be in contact to the pipeline surface for successful motion). However, after several round of experiments using several configurations of the caterpillar wheels of the robot at T-branch, we have concluded that the robot can be able to turn in all pipeline layouts

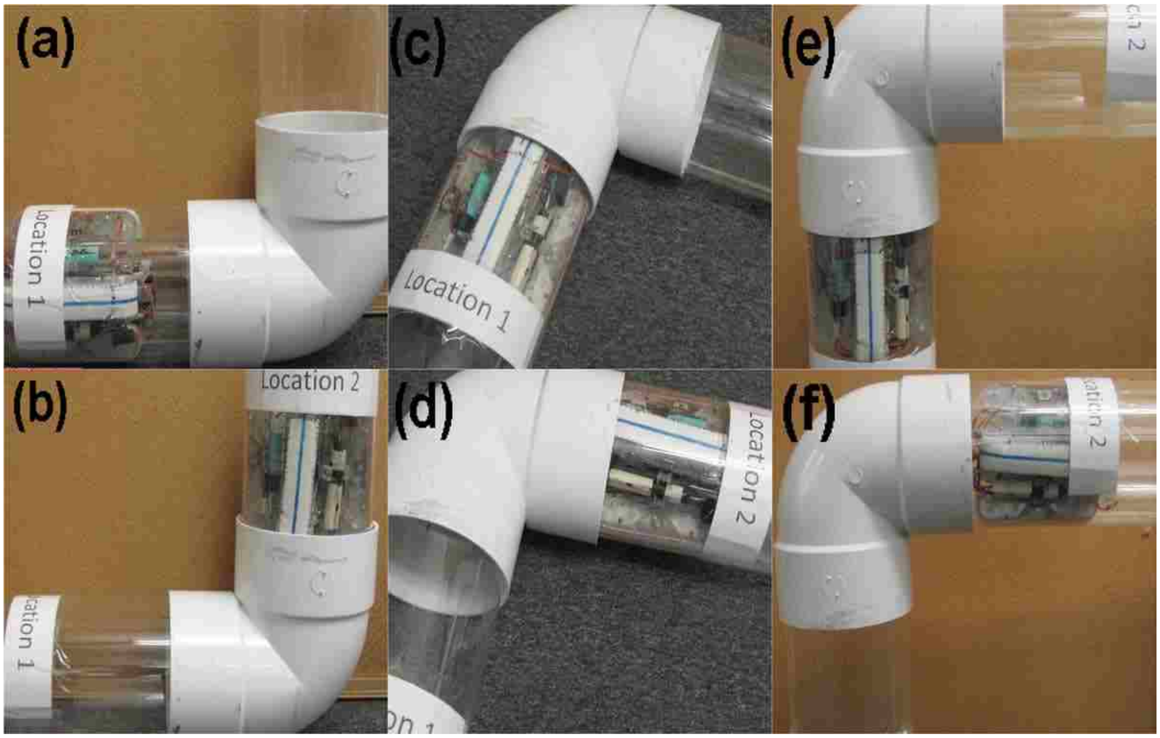


Figure 7.2: Types of motion at 90 degrees elbow, where (a), (b) show H to V, (c), (d) show H to H, and (e), (f) show V to H motion

when at least three caterpillar wheels can manage to be in contact with the pipeline surface as illustrated in Fig. 4.13. Moreover, in the conditions where only two caterpillar wheels can contact the pipeline surface, the robot can turn in all possible configurations except only two caterpillar wheels in the diagonal are in contact with pipeline surface. The problem stems from the fact that the straight caterpillar mechanism does not exhibit the capability of self-adjustability from the position where it cannot able to make a turn (unsuccessful position) to the position where it eventually can make a turn (successful position). Nevertheless, we also observed from the experiments that if the robot can self-adjust to the position where robot can eventually make three or more of its caterpillars contact the surface, then it can change direction at T-branches.

- **Solution of singular motion.** To cope with the motion singularity problem discussed above, we have designed 5 degrees tilted caterpillar-based robot where each caterpillar is tilted 5 degrees with respect to the robot body frame as shown in Fig. 4.3instead of straight caterpillars.

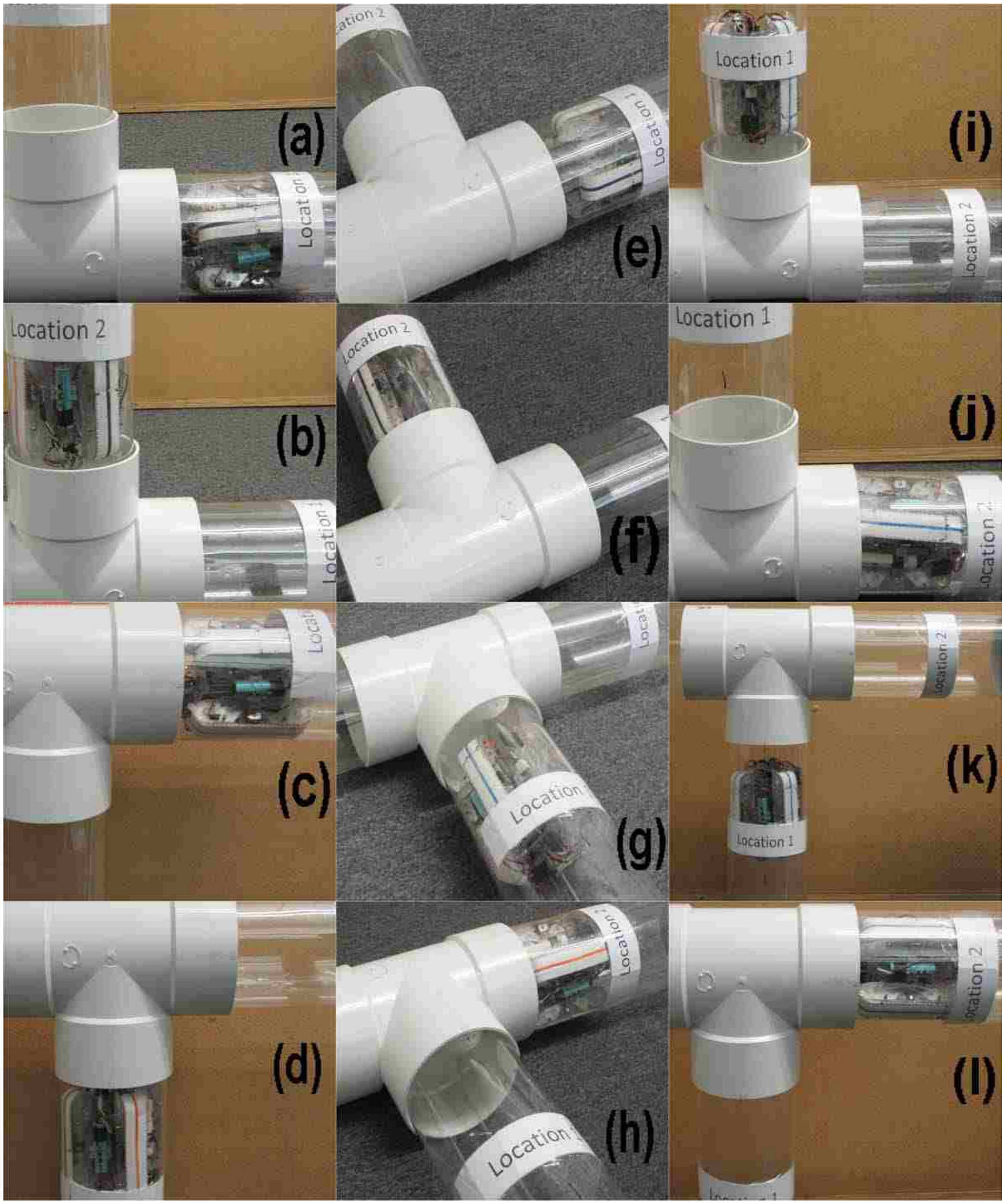


Figure 7.3: Types of motion at T-branch, where (a)-(d) show H to V, (e)-(h) show H to H, and (i)-(l) show V to H motion

The tilted caterpillar performs equally well in comparison to the straight caterpillar in no motion singularity condition as well as it aids the functionality to overcome motion singularity problem whenever needed. In motion singularity conditions, the tilted caterpillar provides

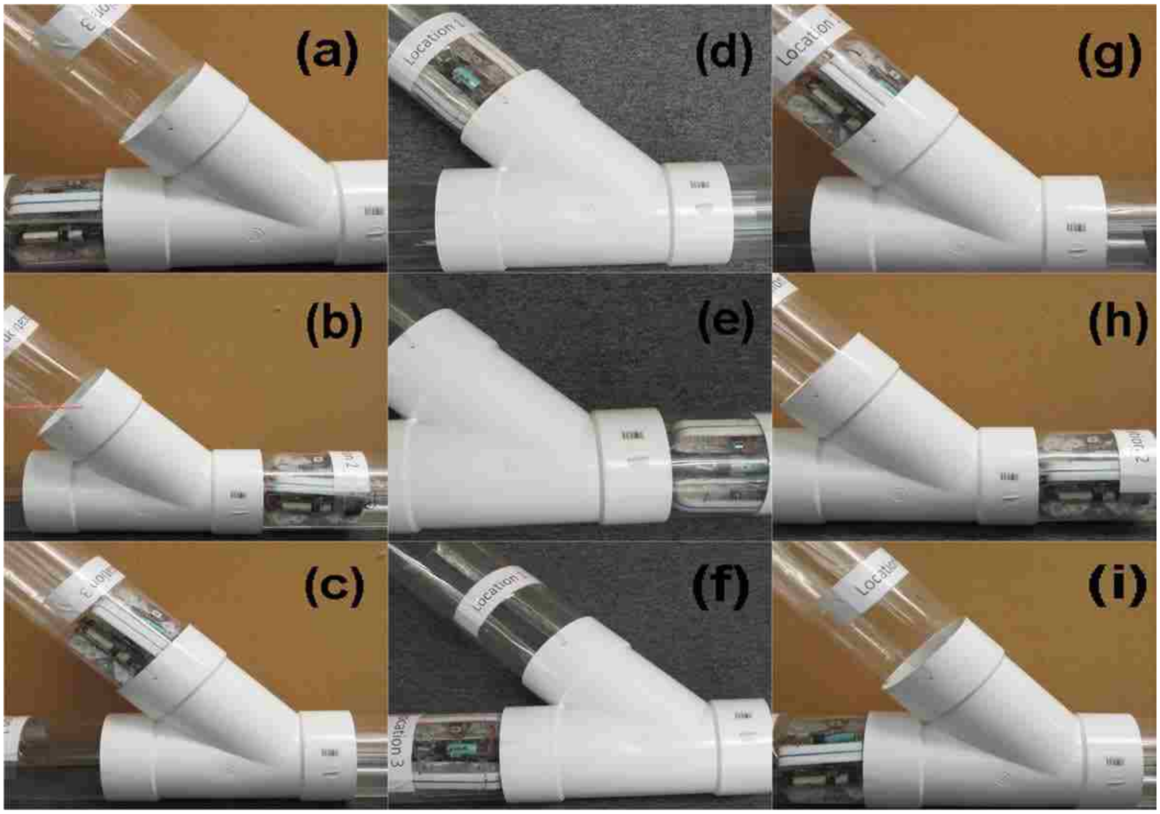


Figure 7.4: Types of motion at Y-branch, where (a)-(c) show H to V, (d)-(f) show H to H, and (g)-(i) show V to H motion

the functionality to self-adjust the robot position in the pipeline bends so that three or more of caterpillars can eventually get in contact to the surface as depicted in Fig. 7.6. This can be achieved from the spiral motion provided by the tilted caterpillars. From the mechanical test, we proved the concept of self-adjustability on how the 5 degrees tilted robot self-adjust to a successful position from an unsuccessful position in a T-branch of the pipeline.

7.2 Performance Evaluation on the System

To validate and check the major features of the SPRAM System , different pipeline topologies have been used. One of those topologies used in the validation is presented in Fig. 7.7a. It comprises linear segments, horizontal and vertical L-bends to demonstrate the capability of the robot to cope with complex environments. The pipeline used for the validation is a 150mm sewer pipeline to

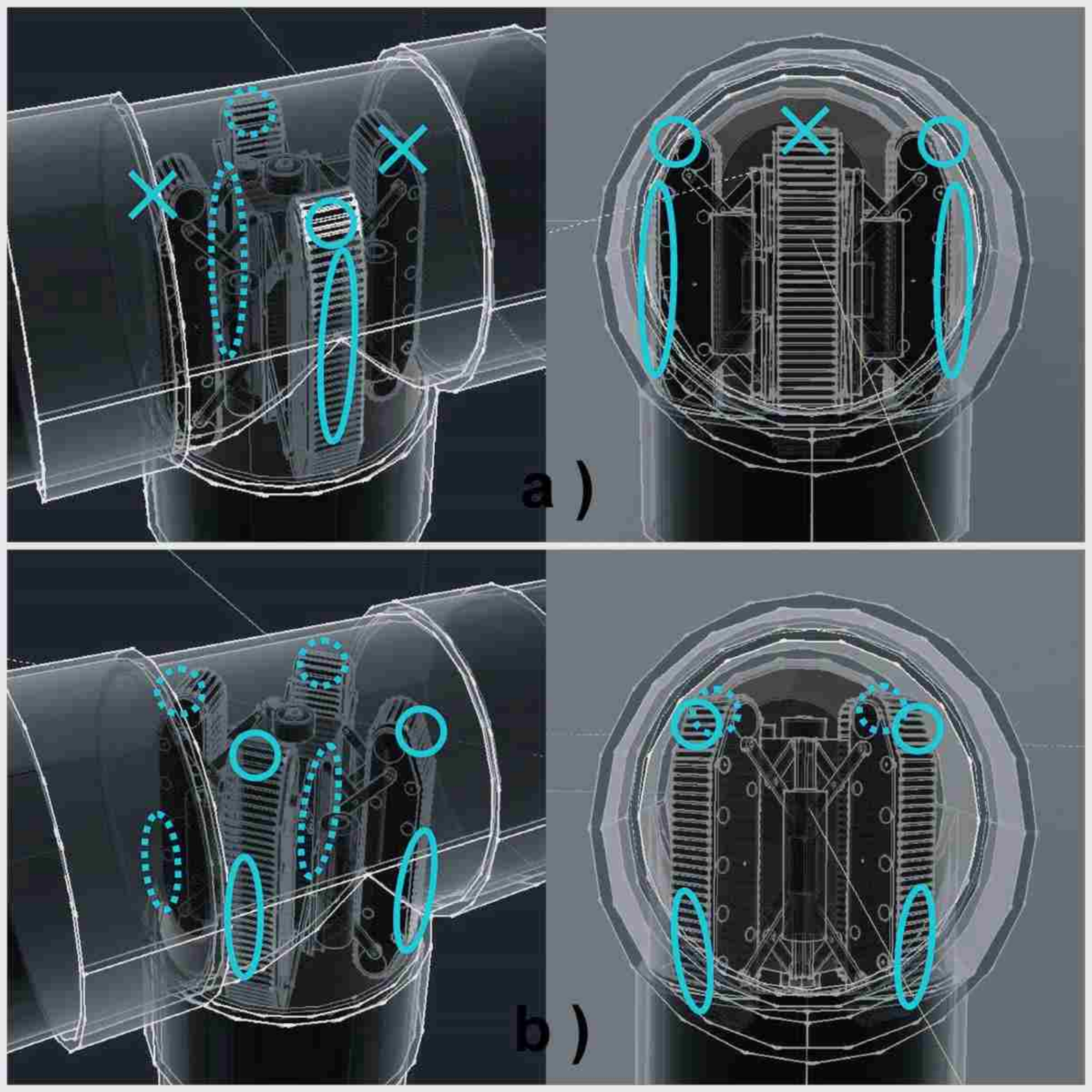


Figure 7.5: Motion singularity problem, where (a) depicts singular motion and (b) depicts successful motion

which a McRAIT-based marker is attached every 500mm. The robot mission illustrated by Fig. 7.7c and Fig. 7.7d allows the robot to perform horizontal and vertical motions.

To validate the performance of SPRAM System several simulation experiments have been conducted. The objective of the simulation was, first, to analyze the marker occupancy size over time and inspections; second, to estimate the maximum range and relative errors in the McRAIT-based localization; and third, to compare the efficiency of the SPRAM System with respect to a system that does not use mobile sensors and builds on a different localization scheme.

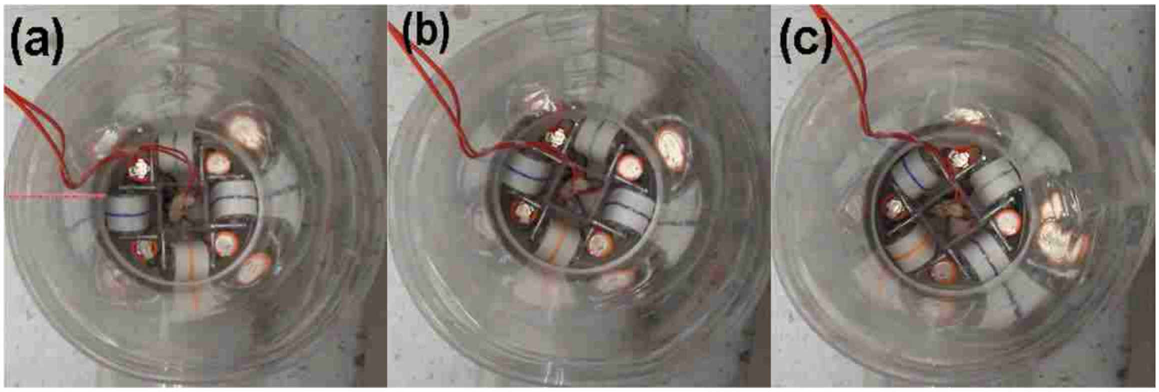


Figure 7.6: Self-adjusting from motion singularity position to successful motion position


(a) A pipeline topology
(b) A robot agent
(c) Robot performing horizontal motion
(d) Robot performing vertical motion

Figure 7.7: Illustration of a pipeline topology and a prototype robot mission

The illustration of the pipeline system used in the simulation experiments is given in Fig. 7.8. It consists of 26 pipeline segments, one upstream station, and one end pumping station. We assume that the fluid carried by the pipeline is flowing in the direction as indicated by the arrows. We also assume that each marker has limited capacity (only 2KB × the number of tags in the related McRAIT system) to store history and incident information during the pipeline inspection. The mobile sensors are drifted to the pipeline from the upstream station and transported by the fluid through the pipeline. The drifted mobile sensors are collected at the exit of the pipeline and their storage is uploaded to the end pumping station further processing about incident localization and pipeline health information collection. The incidents within the pipeline are artificially created at random locations to simulate the actual pipeline environment evolution.

In the experiments related to the marker occupancy, we first derive the optimal values of the number of markers that should be installed per segment in the pipeline (denoted by s/s), the

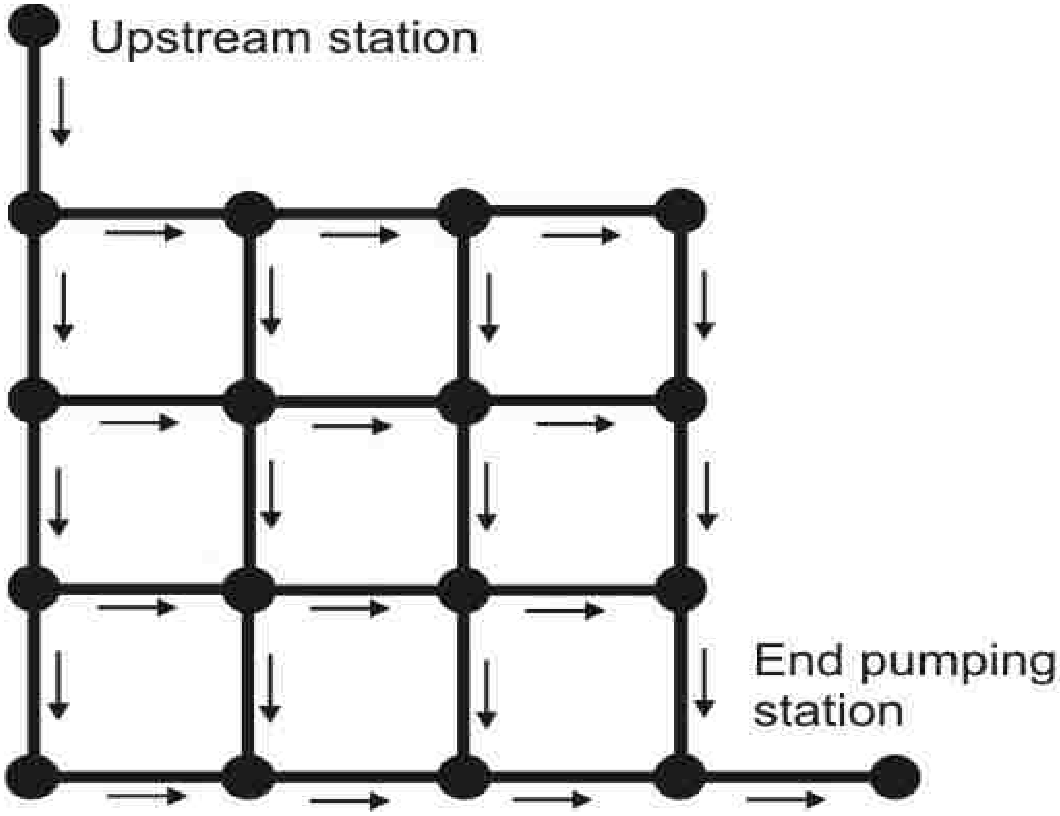


Figure 7.8: Illustration of a pipeline system used in experiments

number of tags per marker (denoted by m), the number of inspection history information that can be accommodated (denoted by H), the number of mobile sensors (denoted by n) used in a mission, and the number of hops (denoted by *Hop*) that are used to store the incidents information when they are detected. The number of hops is measured in terms of the number of successive markers found between the incident location and the actual marker where the incident information is stored.

In order to estimate the optimal values of s/s, m, H, n, and *Hop* values, we develop an algorithm that allows the mobile sensors drifting inside the pipeline and arriving to a junction to randomly select one of the available directions and write randomly on two among the markers available on that segment to store their identity. If an incident is detected during inspection and the memory entries of the markers in the vicinity of the detecting mobile sensor are full, then the data is stored in the next available marker, provided that the distance to that marker can be reported in the event location field (in our experiments it is equal to 6) of the RFID event structure. Indeed, the algorithm assumes that the detecting mobile sensor tries to write in the first available marker until

Hop/2. If no marker is available within this range, a next marker is randomly selected among the next *Hop/2* markers and the information is written on it, by overwriting the oldest entry, if needed.

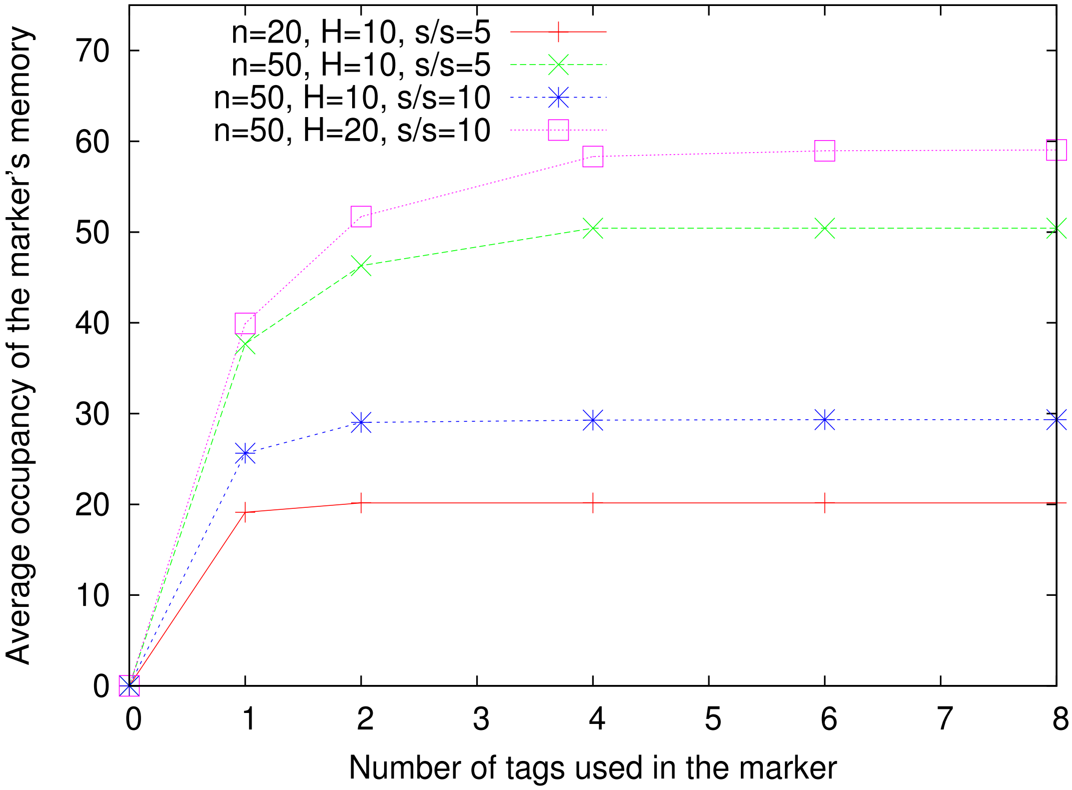


Figure 7.9: Average occupancy of the marker storage for different parameter settings and $Hop = 6$

Fig. 7.9 shows the average occupancy of the McRAIT systems installed in each marker in the pipeline. It shows that the load of the McRAITs increases with the number of histories (H) related to inspection missions and the number of mobile sensors (n) used for inspection. In addition, we notice that for a fixed number of mobile sensors, the McRAIT load increases significantly with H and decreases with the number of markers/segment (s/s). This shows the trade-off between the load and the product $H \times (s/s)$. Moreover, Fig. 7.10 shows the average occupancy of messages in McRAIT systems with different values of H. In sum, the two figures demonstrate that the storage space of a marker (or the number of tags per marker) is determinant for the history the system needs to keep in memory. In particular, only 4 tags are needed to provide an occupancy under 60%, when there is no need to memorize more than 20 inspection missions.

Fig. 7.11 shows the 3D graph depicting the load of all the 4-tag-McRAITs installed on the

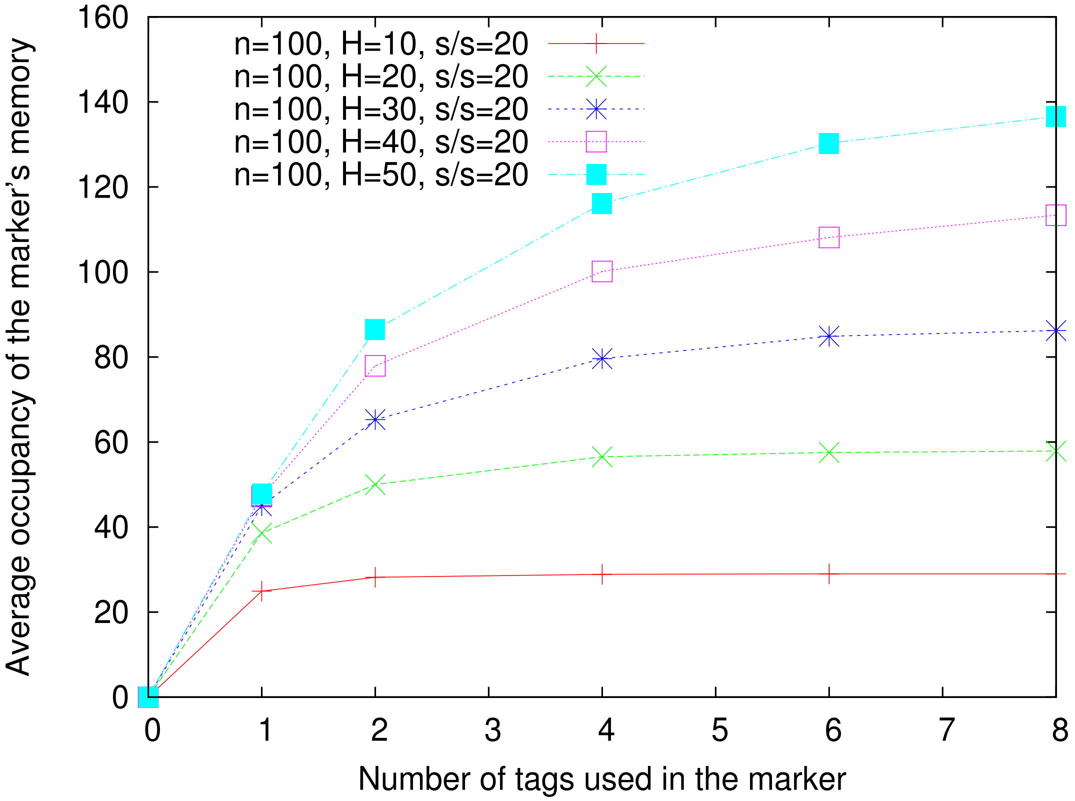


Figure 7.10: Average occupancy of the marker storage for different history settings, and $n = 100$, $s/s = 20$, and $Hop = 6$

markers when 12 incidents are randomly generated and 50 mobile sensors are used, assuming that $H = 5$, $s/s = 10$, and *Hop* = 6. The figure demonstrates that the markers located just after the incidents have higher load and that the following markers have decreasing loads with the distance separating them from the incident.

The second set of experiments aimed at estimating the maximum range and relative errors in the McRAIT-based localization. Fig. 7.12 shows the maximum forward-link-limited range ($D_{forward}$) estimation between an RFID reader and a marker for an ideal isotropic antenna, a dipole antenna with gain 2.2dBi, and a directional antenna with gain 6dBi for the various transmitted power of the RFID reader. The figure demonstrates that for the system to be effective using the state of the art tags, the distance between two consecutive markers should be smaller than 14 meters. This distance can be improved by increasing the transmitting power of the RFID reader and the tag capacity to react.

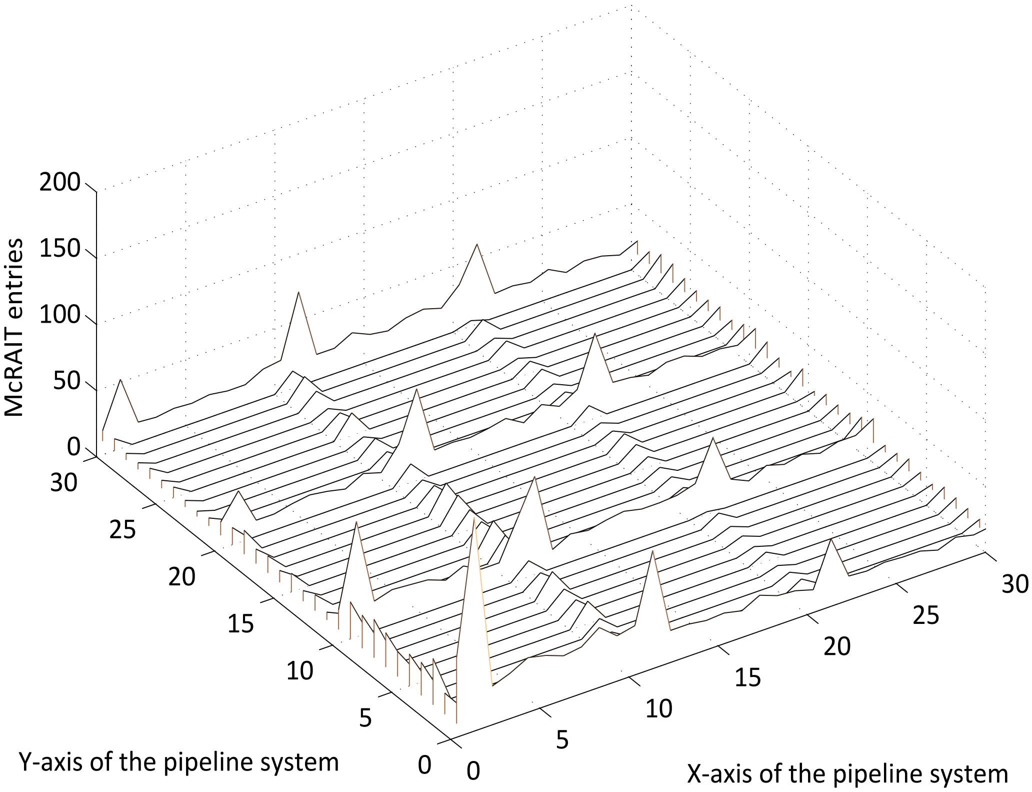


Figure 7.11: Measured RFID entries concentration for 12 incidents using 4-tags-McRAITs with values of n = 50, H = 5, s/s = 10, and Hop = 6

Fig. 7.13 shows the variation of maximum relative error $\frac{\Delta r}{r}$ on the reported distance with the variation of threshold angle θ_0. It shows that when θ_0 is smaller than 25 degrees, the error is smaller than 10%. It is even smaller than 4% when θ_0 is lower than 15 degrees. The relation between the diameter of the pipeline L and the distance d from which it has to contact the next closest tag for different threshold angles is given in Fig. 7.14. One can notice that for $\theta_0 = 15$ degrees, the distance should be around $3.7 \times L$. Fig. 7.15 depicts the relation between the average error (Δr) made on the reported distance and the number of incidents in the pipeline, assuming the distance between two markers in the pipeline is 1000mm, pipeline diameter is L = 150mm, and mobile sensors are drifting at 50mm above from the bottom of the pipeline. The figure shows that when the number of incidents grows from 0 to 100 the average is increasing. This average remains constant for numbers of incidents higher than 100, despite the value of θ_0. In other words, the figure demonstrates that the number of incidents has no effect on the average value of the error

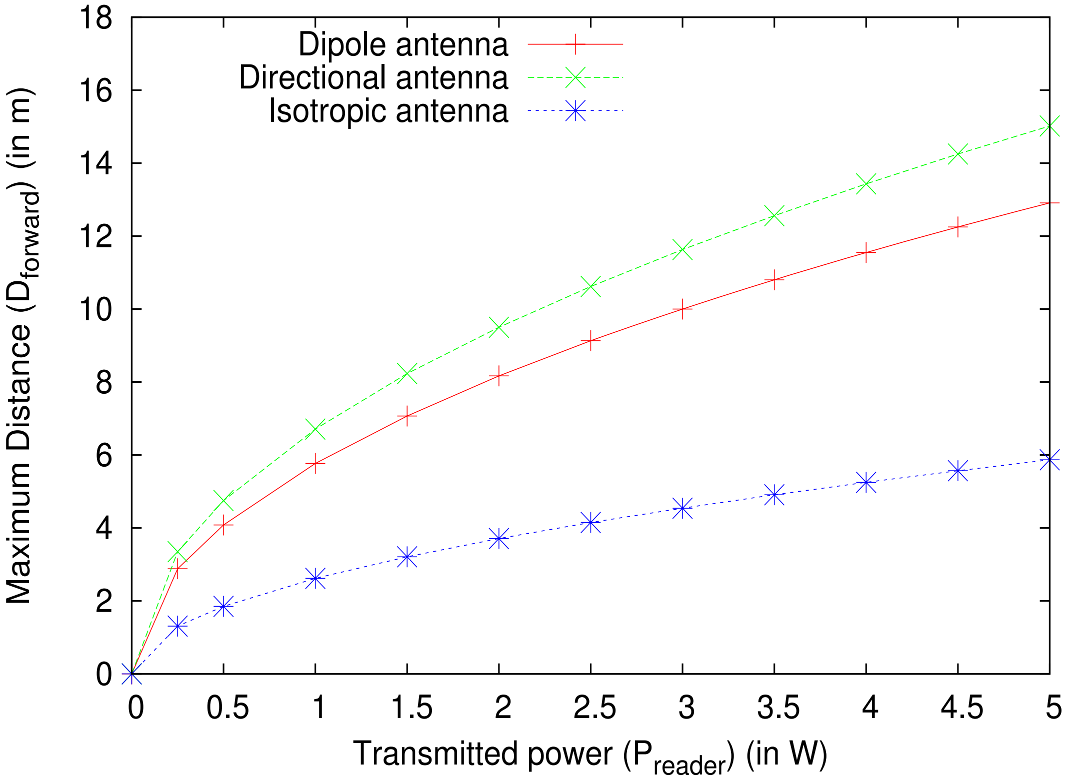


Figure 7.12: Maximum limited radio range between a reader and a marker for different transmitted power

made on the localization distance to a marker.

The third set of experiments aimed at comparing three strategies that can be implemented by the robot to find a reported incident. The strategies are: (a) the robot is aware of the incidents position (as provided by our system); (b) the robot applies the depth first strategy to locate the incident; and (c) the robot attempts random walk. The major parameter used in the comparison is the number of segments traveled from the upstream station made by the robot to find the reported incidents. To achieve a significant comparison, the random walk strategy is repeated several times (1000000 random samplings) and the distance computed is the average number of segments traveled. The distance reported for the depth first-based strategy is also the average of the distances needed to reach all incidents located at the same segment count with respect to the upstream station. Fig. 7.16 depicts the comparison of the number of segments needed to travel by the robot agent for a grid pipeline having 10 per 10 segments. We can notice that our approach gives the least distance to

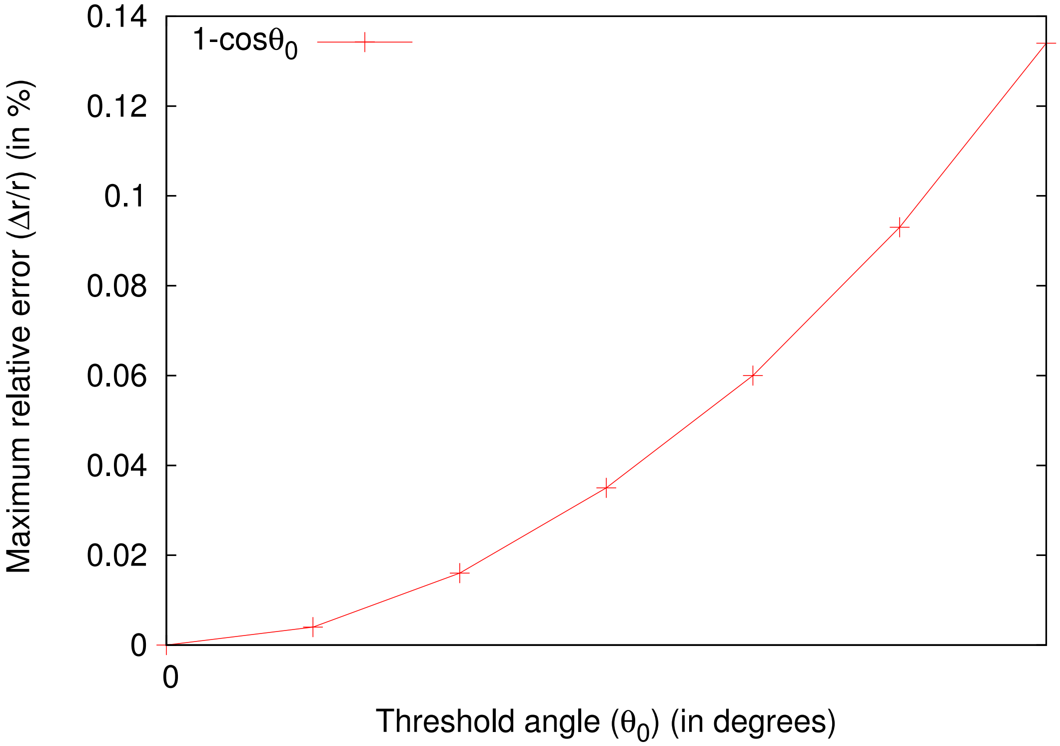


Figure 7.13: Maximum relative error vs. threshold angle plot

perform (since the graph is the bisector of the first quadrant). The other two methods compute an average distance that is very high compared to our method.

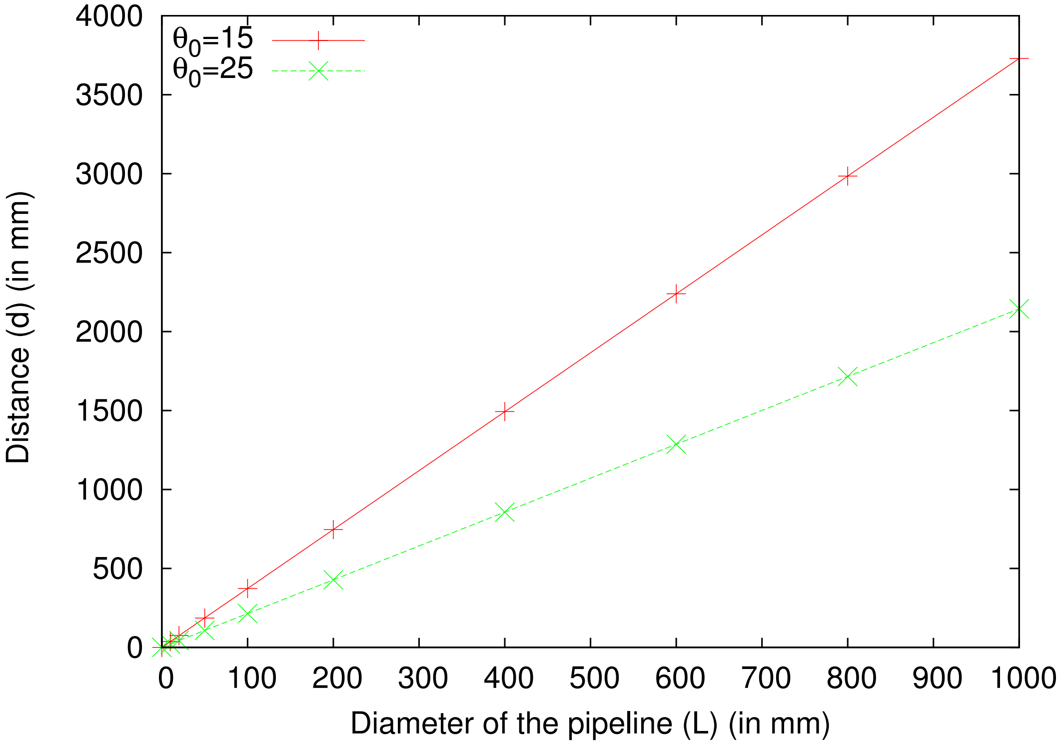


Figure 7.14: The relation between distance d and diameter L of the pipeline

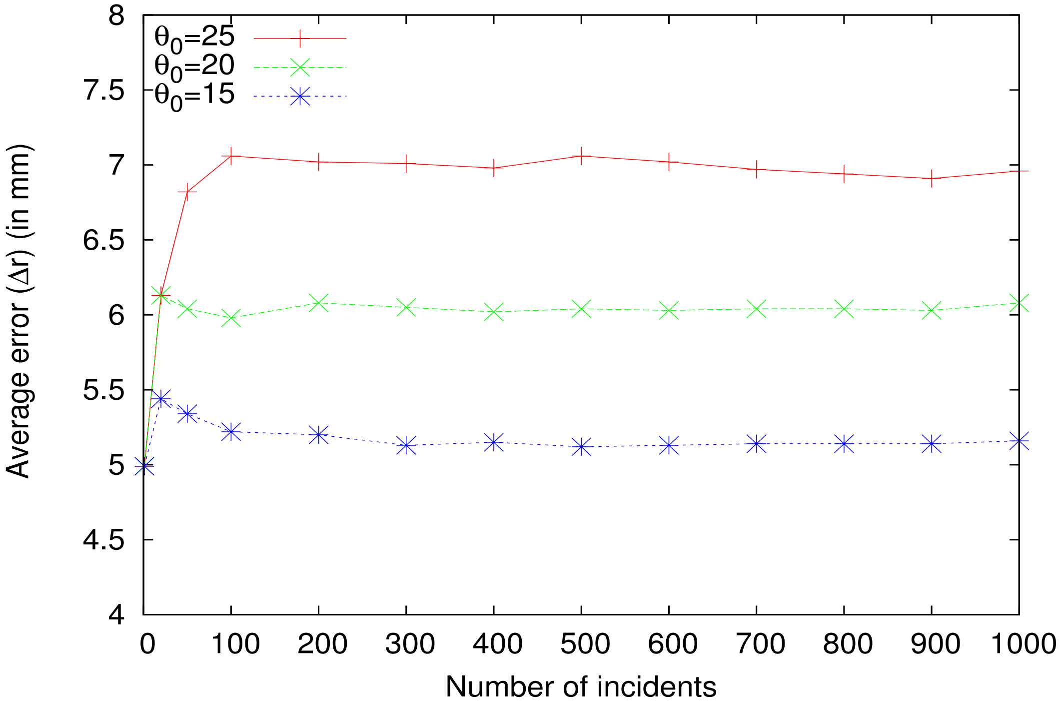


Figure 7.15: Effects of the number of incidents on the average error made on the reported distance

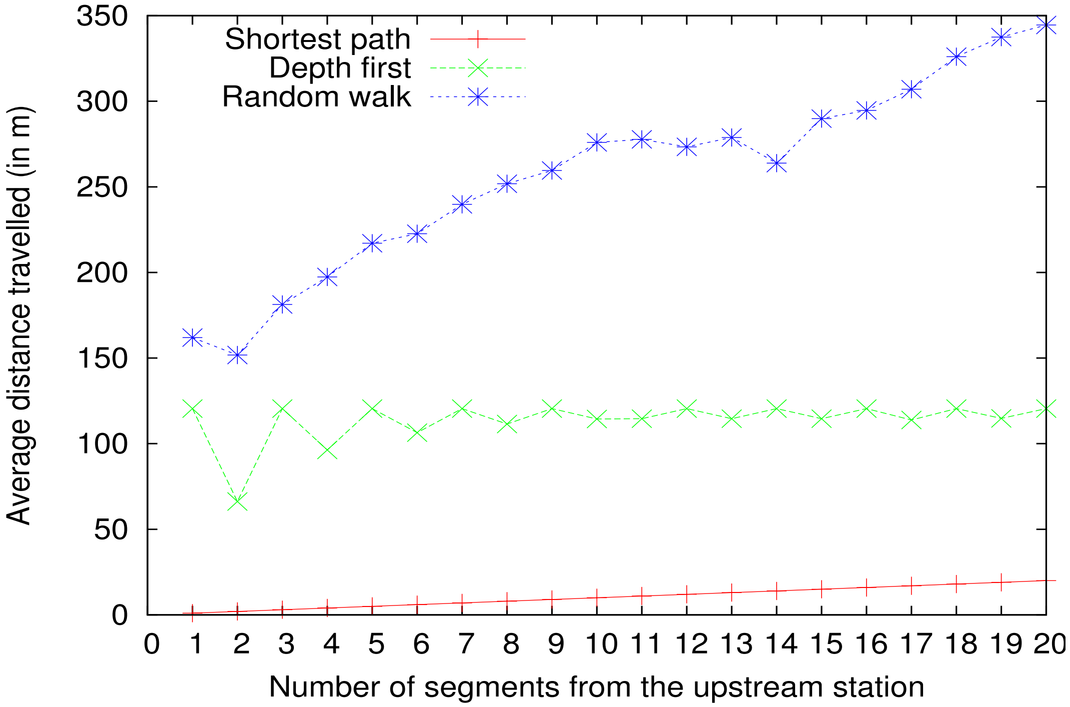


Figure 7.16: Comparison of the average distance the robot agent travels to find reported incidents using three strategies

Chapter 8

Conclusion

In this chapter, we first highlight our contributions of this dissertation. Then, we describe limitations and challenges of this research study, and present open issues for future works. Finally, we conclude the dissertation.

8.1 Contributions

In this dissertation:

- We proposed a RFID-based localization technique which can be applied to large variety of pipeline systems. It allows controllable localization errors in the sense that the threshold it reaches is controlled by a fixed fraction of the distance separating two successive localization markers.
- We introduced a new structure for a powerless storage system (the McRAIT) using multiple channeled redundant array of RFID tags to increase detectability by sensors and agents, storage capacity, and fault-tolerance of tags and communication.
- We designed a scalable mobile sensor architecture which integrates a number of sensing functions, a configurable transmission function, and communication functions with the McRAIT. Scalability allows the sensor architecture to cope with the pipeline nature, RFID systems,

propagation features, and sensing functions. Configurability allows the mobile sensor to cope with the propagation models related to the environment inside the pipeline. The use of redundant sensors helps define a scheme that makes the time, to perform a sensing job in the pipeline network, relatively short and allow higher level of processing compared to the available sensor solutions.

- We designed a prototype model of an autonomous, topology-aware robot agent with different sensing functions and actuators to perform detailed inspection and react to the detected incidents for corrective monitoring. It uses tilted and segmented caterpillars to overcome *motion singularity problems* [39] that may occur in the pipeline bends (e.g., T-, or Y-bends). This prototype extends the agent we proposed in [34, 37].
- We showed the cost-effectiveness and scalability of using a monitoring system based on mobile sensors, robot agents, and multiple channeled redundant array of RFID tags for localization, monitoring, and maintenance of pipeline systems.

8.2 Limitations, Challenges, and Open Issues

The SPRAM System has demonstrated the feasibility and outstanding performance in comparison to existing pipeline monitoring systems, and also showed its cost-effectiveness and its scalability in chapter 7. However, the SPRAM System proposed in this dissertation has some considerations of the limitations, challenges, and open issues faced for flawless system on real world implementation. This section narrates those considerations in each major component of the SPRAM System.

First, we need to develop unfinished features of the robot agent. One of the features is that the robot agent is liquid resistant irrespective of the type of liquid, which is essential for real world implementations. We should consider making the robot agent water liquid resistant in different types of liquids as well as pressures in pipeline. And, the robot agent should provide secure mobility in different pipeline environments such as sizes, pipe materials, goods transported by pipelines, pressures, etc. We may need to develop different types of robot agents for different conditions in pipeline network. And, one of big challenges on a robot agent is the recovery actions. There must be huge demands and numerous difficulties for different environments and tasks which can be endless challenges for a robot agents. In addition, the robot agent needs sensitive and powerful sensors for detail inspection so that quality of inspection can be guaranteed, and also it needs energy efficient components and powerful battery for increasing mission range of the robot agent.

Second, we should explore more on mobile sensors for many challenges. One of challenges is buoys. We need to develop various types of buoys which provide not only protection of the components of the mobile sensor but also increase efficiency of inspection during its operation. In addition, developing various types of sensors are required for increasing performance of mobile sensor inspection.

Lastly, we should implement McRAIT architecture so that the performance improvement of the fixed sensor of the SPRAM System can be proved as well as it can be used on many other RFID applications. And also, we need to keep research on noisy handing of RFID communication in metal-pipelines and in different types of liquids. It will increase efficiency of event location of the system. In addition, we should consider combining McRAIT and traditional sensor networks so that the limitations of the fixed sensor in the SPRAM System can be overcome.

With all above considerations, we believe that the SPRAM System can be the best solution for pipeline monitoring and maintenance system. Therefore, we believe that the further exploration towards the aforementioned direction make SPRAM system proposed in this dissertation more useful in different many real-world scenarios.

8.3 Dissertation Summary

In this research, we proposed a novel cost-effective, scalable, customizable, and autonomous sensor-based pipeline monitoring robotics system, called the SPRAM System. It combines robot agent-based technologies with sensing technologies and RFID technology for efficiently locating health related events and allowing proactive and corrective maintenance of a large spectrum of pipeline systems. Our contributions include an efficient technique for localization, fault-tolerant system for information storage and localization support, and the design of an autonomous 4-caterpillar robot. Experiments along with the prototyping activities demonstrate the feasibility and outstanding performance of the SPRAM System in comparison to existing pipeline monitoring systems, its cost-effectiveness and its scalability.

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Vita

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