World Transactions on Engineering and Technology Education
Vol.12, No.3, 2014

Systematic design of a robotic scanner for industrial pipelines

Constantinos Stergiou†‡ & Alexandros Lagonikas†‡

Technological Educational Institute Piraeus, Athens, Greece†
Kingston University, London, England, Unite Kingdom‡

ABSTRACT: A step-by-step systematic approach to the design and development of a novel modular multi-directional mobile robotic scanner for industrial pipelines is presented. A robotic scanner has been designed to inspect a pipe's structural integrity for potential defects throughout its profile, by attaching it to the outside of the pipeline's insulation. The scanner is enabled to manipulate the pipe inspection around bends and branches, delivering non destructive testing (NDT) for aged metal or plastic industrial pipelines surfaces. The scanning system is capable of longitudinal and circumferential movements, depending on the scanning pattern requirements of each of the NDT methods it utilises. Initial tests have shown positive results in the scanner's ability to move accurately and to find defects and their exact location, especially, in pipeline regions that are inaccessible by traditional means of inspection. A well-established systematic design methodology was used and explained for each step. The use of a systematic design methodology was proved beneficial for the efficient development of such technical systems.

INTRODUCTION

Design methodology is a concrete step-by-step procedure for the design of technical systems that are very useful for increasing the inventiveness of engineers by using systematic procedures to methodologically extend their intuition and experience. Systematic design provides an effective way to rationalise the design process by structuring the problem, establishing stepwise solution principles, and by selecting and optimising them at an early design stage.

The systematic design methodology which was used to provide the optimal working solution is based on the work presented in the book of G. Pahl et al *Engineering Design - A Systematic Approach* (Pahl et al [1]), the VDI Richtlinie (German Engineering Guidelines) 2221, 2222 and 2223.

DESIGN METHODOLOGY

Step 1 - Requirements List

The process, which takes into account all interplay between the various domains of the overall objective, is initiated by the concept design development of a product after extensively recording and categorising the requirements of the product. In the project under study, the design specifications were defined in accordance to the end-user domain needs and the attributes the end-user is looking for.

The mechanical scanner system is generally described as a system to inspect pipes with coating or insulation deployed manually, but one that is capable of simple scanning routines on straight and curved pipes. Although the idea is that most diameters of pipe are to be inspected by the system, it is intended to demonstrate the performance of these devices on pipes of the order of 250-300mm (10-12 inches) diameter including coatings or insulation up to 50mm thick. The recording of the fundamental requirements described through a number of demands and wishes from the end-user perspective resulted in the layout of the design specification as shown in Table 1.

Step 2 - Function Structure

In this design procedure stage, the overall function of the problem is broken down to a meaningful and compatible number of functional requirements (sub-functions) to build the so-called function structure. This breakdown facilitates the subsequent systematic search for solutions.

The functional requirements of the design problem were recorded and categorised to the extent possible. The schematic breakdown shown in Figure 1 depicts the set of main and secondary functions that the scanning system should incorporate in order to cope with the overall function of the project. First, the function to insert the scanner system on the outer surface of the pipe intended for inspection is established (FR1). This requires the handling of a light structure mechanism, as the end-user requirements dictate that the scanner should be easily lifted and handled by a sole worker (FR1A), with certain geometrical characteristics that will facilitate its placement on the pipe (FR1B).

Table1: Requirements list.

Specification		
Changes	(D)emands/ (W)ishes	Requiremenrs
	D	Scanner adjusment to pipe diameter range from 250 to 300mm
	D	Locomotion independent of pipe material
	D	Scanner outer diameter no more than 1m.
	D	Space Provision for sensors: Pulsed EC/ACFM:100x100mm,Radiography:500x400x600mm
	D	Translational locomotion on pipe
	D	Rotational locomotion on pipe
	W	Combination of translational and rotational locomotion
	W	Ability to move pass curved segments of carvature as high as R=1.5Dpipe
	D	Translational Movement accuracy ±2mm
	D	Rotational Movement accuracy ±5deg
	D	Highest Enviromental temperature during operation up to 40°C
	W	Highest Enviromental temperature during operation up to 60°C
	D	Range of Translational Locomotion Speed:10 to 150mm/sec
	D	Range of Rotational Locomotion Speed:1 to 5 rad/min
	D	Overall Maximum Weight:28Kg(in order to be lifted and handled by a single operator)
	W	Overall Maximum Weight for easier transortation:20Kg
	D	Operation under corrosive environments
	W	Rigid structure - No deflection
	W	Functional Safety Monitoring
	W	Low Maintenance System
	D	Intrinsically Safe for Personnel
	D	Obstacel Avoidance of objects as low as 5mm in height,at least 200mm away.
	W	Obstacel Avoidance of objects as low as 3mm in height,at least 300mm away.

Furthermore, an adequate scanning system grip along and around the pipe axis is fundamental (FR2), as it would allow the robot to attach itself firmly and safely to the pipe, while being stationary or when performing the required scanning patterns, without damaging the pipe's outer surface. The robotic scanner must be able to move autonomously along and around the pipe with the required stability and accuracy (FR3). This depends on the means of locomotion that will be incorporated for this particular application, as well as the type of deploying mechanism that is to be coupled with these means. Prior to the scanning process, the intrinsic safety of the mechanism must be ensured against obstacles that the mechanism may encounter on its path, like insulation holding stripes and support columns.

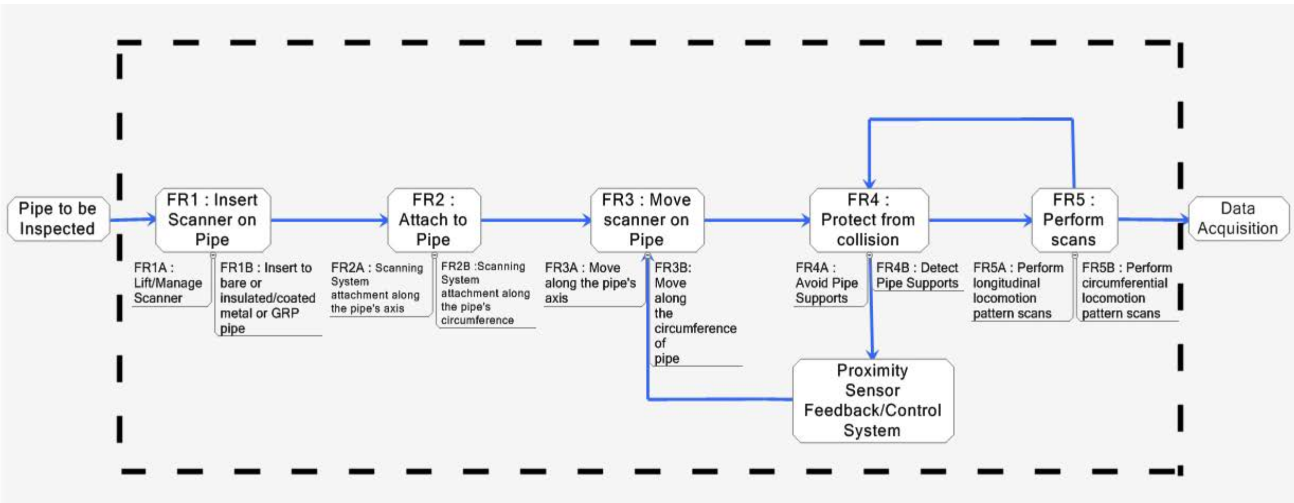


Figure 1: Schematic representation of the function structure.

A function for protection from collision (FR4) has to be implemented in order to detect and avoid these obstacles. Finally, the scanner will perform the necessary scans (FR5) depending on the speed and scanning patterns that each individual NDT sensor demands. Although a software-based solution was to be implemented here, the function was included because, at this stage, it was not clear whether it would affect the overall hardware design solution.

Step 3 - Intuitive Solution Finding

A systematic approach for the development of the concept design is invaluable, as the search for the optimal solution among the numerous prospects of such a project, can be a daunting task for any expert. An engineer's intuition can provide the foundations for a positive outcome but does not always lead to the optimal results by itself. There are ways and methodical procedures that can aid the search for the desirable outcome, not just by adopting new ways of thinking, but also by enhancing the existing methods. In design methodology, a number of different approaches can be proposed. The procedure adopted by the design team is outlined below.

The overall principle solution variants would result from the so called Zwicky morphological matrix [2]. The goal is to produce an adequate number of possible sub-solutions for each sub-function, which after compatible combinations will produce a number of overall viable solutions. The procedure for finding sub-solutions for the main function of the problem; namely, FR3: *move scanner on pipe* will be outlined in detail. This function encompasses the medium of transportation along and around the pipe as well as the means for their actuation. The high number of movable parts and the general complexity of the locomotion process indicate the aforementioned function as the most crucial to the operation, accuracy and reliability of the system.

The procedure was initiated following the intuitive solutions recorded in a brainstorming session. As the next step, a classification matrix is formed in order to produce systematically a number of new solutions additional to the intuitive ones. A selection tool was then applied to reduce the number of possible solutions in order to form the Zwicky morphological matrix. A technical and economical evaluation tool can then be applied to the viable solutions in order to choose the best one.

A series of brainstorming meetings for the main function took place in order to come up with a number of solutions that would serve as the basis for the subsequent systematic solutions approach. Many ideas were expressed, ranging from the very plausible to non-viable, at first glimpse. The concept design sketches shown in Figure 2 give some interesting proposals resulting from the brainstorming procedure. These six concepts were based on the medium of locomotion, while on the pipe's outer surface and the type of actuation the mechanism would require achieving the desired locomotion, translational or rotational. In particular, these concepts were based on 1) normal wheels; 2) mechanical legs; 3) caterpillar type tractors; 4) wheels that are equipped with cylindrical barrels along their perimeter that allow an additional perpendicular axis of freedom (omni-wheels); 5) rails placed along the pipe followed by the scanner; and 6) wheels that are convex shaped as to utilise increased contact surface while moving.

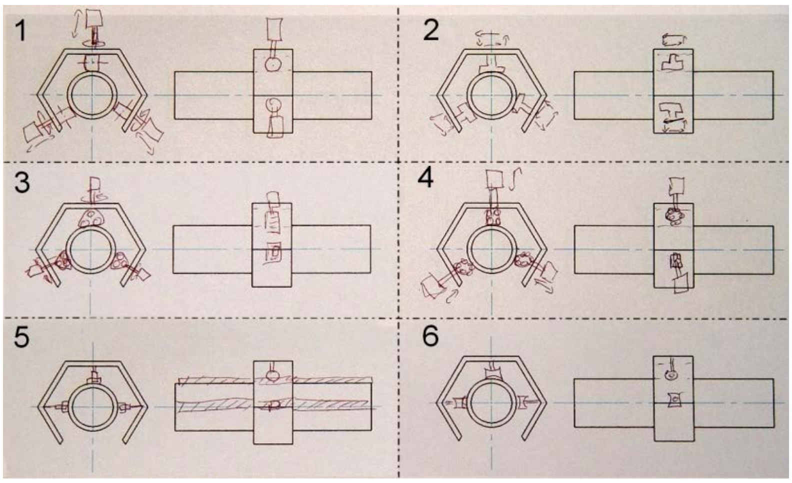


Figure 2: Concept design sketches showing various means of locomotion.

Step 4 - Systematically Generate New Solutions for the Main Function

In order to increase systematically the number of candidate solutions for the main function, and in order to facilitate the categorisation of the various combinations of locomotion types, a two-dimensional classification scheme was assembled as shown in Table 2. Four classifying criteria were selected as the most suitable for analysing the main function FR3: *two on the x* (horizontal) and *two on the y* (vertical) axes respectively. The *locomotion principle* was analysed on the x axis, that is the medium through which the scanner acts and moves on the pipe and it includes all means used in the concept design, with a number of additional ones that emerged during the process of combining possible locomotion solutions.

The *function of actuators*, regarding the role of the actuators in each locomotive module, was analysed on the y axis, into to two general principles in relation to module orientation, which emerged from the need to achieve both translational and rotation movement on the pipe. These were *fixed* and *controllable* orientation of the locomotive units. Each principle encompasses three common types of actuators: pneumatic, electric and hydraulic, as well as a combination of the above and in conjunction with the means of locomotion on the x axis would provide an extensive number of candidate solutions. The six brainstorming solutions were placed in the scheme, and as the next step, new combinations of the classifying criteria were conducted to obtain solutions for the empty matrix cells. The systematic solution search through the use of the classification scheme resulted to additional eight solutions regarding the FR3: *move scanner on pipe* function, and along with the initial intuitive concept design phase, provided 14 plausible solutions.

Table 2: Classification scheme.

Function of Actuators	Actuator Type	Locomotion principle / Medium	Wheel Approach					Tracks on Scanner			Track on Pipe	Walker Approach	
			Magnetic Wheels	Conventional Wheels	Omniwheels	Mecanum Wheels	Convex Wheels	Rigid Tractors	Actively Compliant Tractors	Passively Compliant Tractors	Rails on Pipe	Legs with suspension	Legs using Suction/Vacuum cups
			1	2	3	4	5	6	7	8	9	10	11
Fixed Orientation of Locomotion Units	Hydraulic Actuators	A											
	Electric Actuators	B			3	5				8			
	Pneumatic Actuators	C									7		2
	Combined Actuator Types	D		1	4		12		11			14	
Controllable Orientation of Locomotion Units	Hydraulic Actuators	E								13			
	Electric Actuators	F	10							9			
	Pneumatic Actuators	G											
	Combined Actuator Types	H		6									

Step 5 - Selection Procedure

A selection chart (Table 3) was compiled to filter the solutions that were viable from those that were not, according to general selection criteria. While every classification sheme solution was deemed viable at a basic level, many would not satisfy the standards set in regards to specifications, intrinsic safety or would be clearly out of budget range. Five of those solutions were found to satisfy all criteria and were ready for further evaluation process. These five solutions were: 1) conventional wheel modules, fixed orientation with a combination of electrical/pneumatic actuators (solution #1); 2) Omni-wheel modules of fixed orientation and actuated by electrical motors (solution #3); 3) conventional wheel modules, controllable orientation and with a combination of electrical/pneumatic actuators (solution #6); 4) passively compliant tractors, fixed orientation and actuated by electrical motors (solution #8); and 5) passively compliant tractor modules, controllable orientation actuated by electrical motors.

Step 6 - Systematically Generate New Solution Principles for the Overall Problem

In this step, a Zwicky morphological scheme was assembled (Table 4) for the purpose of a systematic overall solution finding. A two-dimensional matrix was built, where on the first column the functions of the function structure scheme were placed. For each function, possible solutions were placed in the corresponding row. For FR1: *insert scanner on pipe*, the solutions vary among a structural frame that would be one-piece made in a CNC machine, a set of interconnected aluminium bars/profiles, a chassis that would be comprised of two identical parts that would be connected but could *unclip* to be attached to the pipe and, then, *close* again, a one-piece chassis that would probably be made by water jet cutting and a design, which would incorporate two identical developed structural frames, which would be connected in a way that one part could lead/guide the other.

The possible solutions for the function FR2: *attach to pipe* are given in the next row. It was decided early that it would be critical to have as much gripping capacity from the system, while retaining the lowest number of necessary components. Two locomotion modules would be insufficient for attachment and locomotion on the pipe, while more than three would introduce redundant complexity to the mechanism's operation and control. The most critical function, FR3, includes the five aforementioned solutions resulting from the classification scheme and selected through the selection cart as shown in the previous step. The function FR4: *protect from collision*, included the sensors electrical components that provide the feedback of collision detection in case of an obstacle.

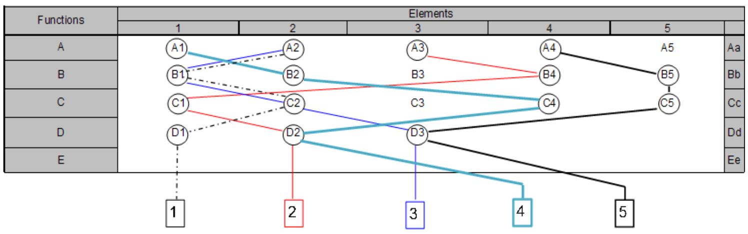
Table 3: Selection chart.

Selection Chart								
Solutions	Assesment of the various solutions according to the selection criteria: (+):yes,(-):no,(?):lack of information,(!): specifications check for changes							Verdict
	Viability of solution	Solution in accordance ot the specifications	Components that can be manufactured "in situ"	Cost efficient	Safety	Delivery time for main required components		
	A	B	C	D	E	F	Notes	
1	+	+	+	+	+	+		+
2	-						A:Locomotion Stability on Complex Surface Issue	-
3	+	+	+	+	+	+		+
4	+	+	+	+	-		E:Low traction can cause fall	-
5	+	+	+	-			D:Only custom made for the application,expensive	-
6	+	+	+	+	+	+		+
7	+	+	+	+	-		B:Requires position of tracks on pipe,not Autonomous	-
8	+	+	+	+	+	+		+
9	+	+	+	+	+	+		+
10	+	-					B:Interaction with NDT sensor fields	-
11	+	+	-				C:Complex non fail safe mechanism	-
12	+	-					B:Problems with small obstacles on pipe	-
13	+	-					E:Large/heavy Actuator unit volume	-
14	+	+	+	-			B:Complexity of Control	-

Function FR5 was included provisionally in the function structure, but during the overall solution-finding, it was evident that it would not affect any aspects of the scanners electromechanical design either technical or economical and, consequently, there was no need to combine it with any solutions from the other functions. The sub-solutions for each function were combined in terms of compatibility and efficacy. In this way, the Zwicky morphological matrix provided five overall solutions that theoretically had the potential to satisfy all the demands from the requirements list and most of the wishes documented.

Table 4: Zwicky matrix for overall solution finding.

Functions		Elements					
		1	2	3	4	5	
A	FR1:Insert Scanner on Pipe	One-Piece Chassis machined Chassis	Aluminum Profile uniform structure	Two Part "Hinge" Design	WaterJet Cut Chassis	Two-Part:"Leeding Part - Following Part"	a
B	FR2:Attach to Pipe	Grip Radially with Electic Actuators	Grip Radially with Hydraulic Actuators	Manual Grip	Tighten Circumference with Belt	Grip Radially with Pneumatic Actuators	b
C	FR3:Move scanner on Pipe	**Solution 1:** Conventional Wheels, Fixed Orientation, combination of electrical/pneumatic actuators	**Solution 3:** Omniwheels ,Fixed Orientation, electrical motors	**Solution 6:** Conventional Wheels, Controllable Orientation, combination of electrical/pneumatic actuators	**Solution 8 :** Passively Compliant tractors , Fixed Orientation , electrical motors	**Solution 9 :** Passively Compliant tractors , Controllable Orientation , electrical motors	c
D	FR4:Protect from collision	Ultrasonic Sensors	Bumpers	IR Sensors	Video image recognition		d
E	FR5:Perform scans						e



Step 7 - Evaluating Solution Variants

An evaluation of those five overall solution variants was conducted according to technical and economic criteria in order for the optimal and final solution to be highlighted. The evaluation that can be found in Table 5 consists of the technical (left), economic (middle), overall (right).

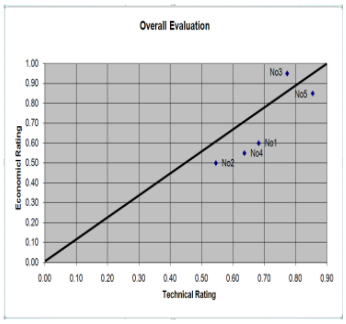
The technical chart utilised specific evaluation criteria and the solutions were evaluated according to a scale from 1 to 4, from worst to optimal. The evaluation system provides a weighted outcome by incorporating higher factors of importance to those criteria that are considered more critical than others, for example, good traction. The final outcome and ranking of weighted results that range from 0 to 1, make clear for the first time, which solutions are favourable and believed to be technically the most probable and efficient. Thus, after a cost evaluation of those overall solutions, the combination of technical and cost effective criteria would reveal the optimal solution.

The economic evaluation chart analyses the different types of costs and ranks the solutions based on their estimated economic value. The above process would ensure the cost effectiveness of the final solution, especially, in cases that two or more solutions were similar in technical efficiency. Finally, the overall solution rating diagram combines data from the technical and economic ratings and provides the overall best and most balanced solution. As a result, the conceptual design stage showed two favourable solutions: No. 3 and No. 5. The first solution involved the use of omni-directional wheels, integrated into an aluminium profile structural frame with three independent modules. Two of the modules were to be used for locomotive purposes, while the other was to be used for attaching the system onto the pipe. The second, which was rated slightly higher incorporates tractor-based locomotion with tracks that rotate every time, there is a need for translational or rotational movement on the pipe. There are three identical tractor motive units, synchronised to perform each kind of motion and also to be able to retract and expand when required for the scanner to attach to the pipe.

Table 5: Evaluation charts.

Evaluation Chart												
	Criteria	Weight	A:No1		B:No2		C:No3		D:No4		E:No5	
			Points (P:Normal Points - (P):Points weighted)									
			P	(P)	P	(P)	P	(P)	P	(P)	P	(P)
1	Good Traction	2	3	6	3	6	2	4	3	6	4	8
4	Safety	2	2	4	1	2	2	4	2	4	3	6
8	Fail safe mechanism	2	2	4	1	2	1	2	2	4	3	6
2	Easy Motion Control	1	1	1	1	1	4	4	1	1	2	2
5	Compliancy to Pipe's Surface	1	3	3	2	2	2	2	3	3	4	4
6	Lightweight	1	2	2	2	2	4	4	1	1	2	2
7	Compact Design	1	2	2	2	2	3	3	1	1	2	2
3	Simplicity in Assembly	1	2	2	1	1	3	3	1	1	2	2
9	Resistance in Heavy Duty Applications	1	2	2	2	2	2	2	3	3	4	4
10	Level of Autonomy	1	2	2	2	2	3	3	2	2	3	3
11	Low Maintenance System	1	2	2	2	2	3	3	2	2	2	2
	Ideal Points: 44Normal - 48Weighted		23	30	19	24	29	34	21	28	31	41
	Weighted Score		0.52	0.68	0.43	0.55	0.66	0.77	0.48	0.64	0.70	0.85
	Rank			3		5		2		4		1

	Criteria	A:No1	B:No2	C:No3	D:No4	E:No5
		Points				
1	Materials Cost	2	3	3	3	4
2	Manufacturing Cost	1	1	3	1	2
3	Assembly Cost	2	1	3	1	2
4	Maintenance Cost	2	1	3	2	3
5	Adjusments Cost	3	2	3	3	4
6	Sum	2	2	4	1	2
	Ideal Points:20	12	10	19	11	17
	Weighted Score	0.60	0.50	0.95	0.55	0.85
	Rank	3	5	1	4	2



The significance of the methodology was validated by the outcome of the project trials on the final test bed, as well as in trials carried out at Drax Power Station - Yorkshire, UK [3].

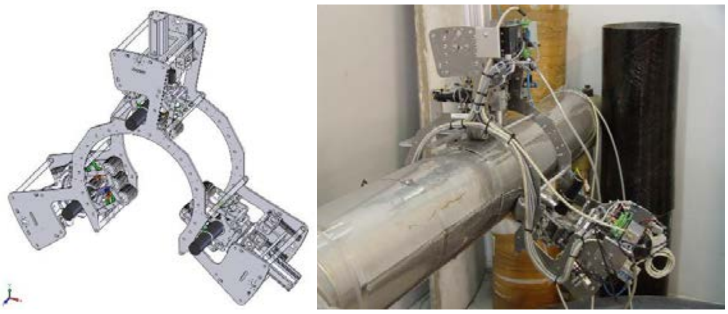


Figure 3: Scanner final solution.

CONCLUSIONS

Assessing the importance of design methodology and how it affects the outcome of a given mechanical design project is crucial, as is the transformation of abstract initial ideas into conceptual solutions and subsequently into technical products that operate in accordance with the demands and wishes outlined on the specified requirements list. It must be mentioned here that it was impossible to record in this article all the systematic procedures used in such a project; thus, only the basic methodical steps were explained analytically.

The design methodology presented is an invaluable tool for enhancing the intuitive engineering skills of engineers, and it can easily be taught to, and implemented by, students. The limited number of initial intuitive conceptual solutions was increased systematically through the shown methodical tools. By assembling the function structure, the functional subsystems were made clear. By compiling the classification matrix for the main function, new design options could be found in addition to the brainstorming (intuitive) ones. By building the Zwicky morphological matrix, a number of the overall solutions could be designed. Systematic selection and evaluation tools led to the best solution.

REFERENCES:

1. Pahl, G., Beitz, W., Feldhusen, J. and Grote, K.H., *Engineering Design - A Systematic Approach*. (3rd Edn), London: Springer Verlag (2007).
2. Zwicky, F., Entdecken, Erfinden, Forschen im Morphologischen Weltbild. Muenchen: Droemer-Knauer (1971) (in German).
3. Chatzakos, P., Lagonikas, A., Psarros, D., Spais, V., Hrissagis, V. and Khalid, A., On the mechanized inspection of glass fiber plastic pipes and pipe joints. Advances in Mobile Robotics - *Proc. Inter. Conf. on Climbing and Walking Robots*, 8-10 September, Coimbra, Portugal (2008).