

Modeling and Simulation of In-pipe Inspection Robot Behavior through Pipeline Fittings

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ABSTRACT — *This research paper is an presentation of author's work to intensify the modeling and simulation of the pipeline inspection robot behavior during his movement through pipeline including both kinematical and dynamical analysis especially in the case of pipeline fittings: like elbows, T-pieces, narrowing and widening points, as well as pipeline ascents and descents under various angles (when the pipeline follows the terrain). For this purpose, robotic architecture was proposed, based on which a CAD model has been developed. Accordingly to this a robot behavior algorithm has been developed, including its mechanical and control part. The research was carried out to see how much the prefabricated robot architecture and due to this adopted control system meet the requirements placed on robot motion through the pipeline. For that purpose, were use combinations of several programs: the 3D CAD program Solid Works and CAE programs: ADAMS and MATLAB Simulink program.*

1 Introduction

Due to their system complexity, because they are configured from different pipe fittings (elbows, T-pieces, narrowing and widening points), pipelines need robots with extraordinary mobility, including the relevant advanced control algorithms to be tested [1]. For the purposes of pipeline maintenance and inspection, in particular its interior walls, a number of researchers have developed quite of lot of robots that are able to move within a pipeline. It is the complexity of the pipeline that defines special conditions of moving through them, which is why there are few developed robots able to easily move within them [2]. Existing robots are normally able to successfully negotiate mainly horizontal pipeline sections, but only some of them are able to fully negotiate complex pipeline configurations, i.e. some of their fittings such as vertical sections, elbows and T-pieces [1]. All these researchers are driven by the idea of developing a robot system that will easily move irrespective of which pipeline fitting it is passing through.

The research presented in this article is an extension of the research presented in Osman and Kovačić, 2017 [3], and will generally be based on such presented architecture for an in-pipe inspection robot with a central motion system based on the screw principle and featuring an adaptive mechanism that provides the necessary pressure of its wheels against the pipeline walls. The motion principle for some of its parts, such as its legs, has been modified. We removed the hydraulic cylinders between its legs and installed electromechanical motion actuators on the leg joints, between its links. The authors believed this would facilitate resolving the issue of controlling the robot and improve its stability and adaptability to varying pipeline diameters and its ability to move through any pipeline fitting, thus also enhancing the overall efficiency of the robot system [3]. We propose a so-called hybrid pipeline inspection robot compliance control system, including its passive and active parts. Force sensors have been installed on the robot legs, which detect contact with the surface (interior pipeline wall)

and actively control the robot actuators. Also, an actuator has been installed in the lower link of each robot leg, which allows for varying legs' passive compliance. As the pipeline interior is a curved 3-dimensional surface, it is very difficult to create a mathematical model, especially in pipeline fittings such as elbows, T-pieces or narrowing points. A crucial issue appearing here refers to the speeds of each wheel, or wheel pair as in [3], of going through the pipeline, as well as the wheels' pressures against the pipeline wall, which are different.

This paper aims to present and establish mathematical models for typical pipeline fittings such as elbows, T-pieces, and narrowing and widening points, which should result in kinematic and dynamic equations for the robot's movement through such fittings. Furthermore, we aim to present a control model based on the control of robot's contact force with the interior pipeline wall. It became obvious while modeling robot's motion through a T-piece that the geometry of this model makes it much more complex than the model designed for a pipeline elbow, requiring additional assumptions and considerations, depending on the direction in which the robot moves through this pipeline fitting. We intended to use the models so obtained to simulate robot motion through the pipeline and its fittings by using a combination of the MSC ADAMS © [4] and MATLAB © [5] computer tools. We expect such simulation would be of great help as a tool by allowing us to conduct a broader analysis of the robot system's behavior, detect any errors in the robot system and in its relevant model, and to optimize the robot's configuration and the mathematical behavior model parameters. If we were to apply both methods concurrently, it would be easier for us to evaluate the robot system, i.e. its architecture and behavior. A mathematical model may be developed by using different analytical methods subject to certain assumptions and approximations required by the complexity of the system, however, simulation is always recommendable as a method of testing a system's behavior and verifying it [6].

Based on the robot architecture presented in [3] and above described modifications in the robot structure, we provided CAD models for each robot component and assembly by using Solid Works ©. The robot CAD model was imported to the MSC ADAMS simulation program, where it creates a CAD model of a complex mechanical system including all necessary properties, kinematic connections and parameters for further kinematic and dynamic analysis. The ADAMS/Control interface connects MSC ADAMS © and MATLAB Simulink ©, i.e. data are exchanged between them. In this case, it is the output based on the relevant robot motion equations - MATLAB Simulink creates a system control block scheme based on such data. During the kinematic and dynamic estimation process, data are exchanged between the virtual prototype and the system control program, where MSC ADAMS and MATLAB Simulink solve the mechanical and control system equations, respectively.

The next Chapter summarizes the research area with a brief review of the known and completed research in the area available in literature in connection with the research presented in this paper. Chapter 3 provides the problem statement which described the authors' motivation to conduct this research including a link to similar completed research and also describes the scientific contribution of this paper. Chapter 4 provides a presentation of the robot CAD model, while Chapter 5 briefly describes the mathematical models of pipeline fittings (elbow 90°, narrowing / widening and T-piece 45°). Next Chapters presents decryption of control algorithm and simulation of robot behavior in programs MSC ADAMS and MATLAB Simulink, while Chapter 8 give the discussion of obtained simulation results. Chapter 9 provides the conclusion of the given research and directions of potential future research.

2 Related Work

Quite a number of articles have been published in scientific literature that address the research into how a pipeline inspection robot behaves while running through pipeline components (fittings) such as: elbows, T pieces, etc. The authors only refer to those they found relevant to their motivation and the research presented below in this paper.

Firstly, we should mention the work of Roh and Choi, 2005 [1] which provides in addition to a presentation and structural description of a pipeline inspection robot named MRINSPECT IV (casings, driving modules and CCD circuit modules) a presentation of the geometry of certain pipeline fittings such as a knee and T piece,

including a separate mathematical model for each of them. Their paper also provides a simulation of the robots movement through them including the relevant movement speed results. The simulation is presented as simply as possible by observing the movement of the contact points on robot's legs against the pipeline wall. The paper also provides a presentation of an experiment conducted with that same robot in such fittings and a discussion of the results.

An extension of this research is found in the work of Roh et al., 2008 [7] which describes the next generation of the same robot type, namely the new model named MRINPECT V. The paper also provides a presentation of its structure, as well as experimental data resulting from measuring how the robot behaves while running through 8" pipeline fittings (in the horizontal and vertical sections of the pipeline, horizontal and vertical 90° keens with 1.5 D, and horizontal and vertical T piece). It also provides a discussion of the power efficiency depending on the selected robot drive mode.

Authors Ciribea et. al., 2010 [8] in their paper present a robot for pipe inspection and exploration, which has in its structure a module for the maintenance of a constant pressure force between the robot's wheels and the inside diameter of the pipe (mini robot with active structure adaptable to the pipe diameter). In paper is also presented mathematical model of DC motor, sensor model with DC motor torque control with PID algorithm. Simulation is made in MATLAB Simulink program.

Another paper we would like to mention is that by Nishimura et al., 2012 [9] and an extension of that research in a paper by Kokagawa et al., 2013 [2], where in addition to the structure of a pipeline inspection robot moving according to the screw principle they present an experiment and the results of measuring the robot's movement through pipeline fittings (knees and T pieces). The experiment was conducted in a pipeline with PVC fittings. A particular emphasis was placed on the robot's passage through a T piece. The experiments were conducted on a pipeline having an interior diameter of 125 mm. As part of the results discussion, the authors addressed certain issues arisen during the experiment.

Kang et al., 2013 [10] presented in their paper the development of a pipeline inspection robot named PAROYS, including its design and simulations in pipeline branches, especially while running through T pieces.

We should also mention the work of Ciszewski et al., 2015 [11] who presented in their paper the development of a pipeline inspection robot with an adaptive drive positioning system and described its design, as well as the presented mathematical kinematic robot models. The paper also provides a simulation of the robot's behavior by using the Autodesk Inventor Dynamic Simulation tool and presents an experiment on robot's behavior. In paper [12] of the same authors we can find presentation of research for modeling and simulation of a tracked mobile robot for pipe inspection with usage of MATLAB (with Robotic Toolbox) and V-REP software.

At the end of this chapter it is important to mention that in scientific literature is a lot of articles which presents research of cooperation between ADAMS and MATLAB Simulink program with the purpose of connecting the kinematic and dynamics algorithms of system behavior with control algorithm as a verification process. Here we would like to mention some chosen papers from the authors Brezina et. al., 2011 [13], Angel et. al., 2012 [6], Zhonling et. al., 2015 [14], Gao et. al., 2016 [15], Ilgen et. al., 2016 [16] and Huang et. al., 2017 [17]. According to the author's opinion, the above works present the mentioned approach in a series of various examples of mechatronic systems.

3 Problem Statement

As mentioned in the introduction, the research presented in this paper is an extension of the research presented in the relevant article by Osman and Kovačić, 2017 [7] and the development of the robot's CAD model will use the architecture based on that presented pipeline inspection robot architecture, with certain minor changes to be described in the next chapter.

What particularly motivated the authors is the challenge to present and establish a mathematical model for the typical pipeline elements (knee, T piece, narrowing and widening sections) and to use that as the basis for

deriving kinematic and dynamic equations of robot's movement through these elements. Furthermore, the aim is to use these equations obtained to present the robot control model based on controlling the force of contact between the robot and the interior wall of the pipeline.

Such models are intended to be used to simulate the robot's movement through the pipeline and its elements by using a combination of the Solid Works, MSC ADAMS and MATLAB Simulink software. The authors believe that such simulation would be of significant help to them as a tool to allow them a broad perspective of the robot system behavior and thus also allow them to detect any errors both in the system architecture and in its behavioral model. This would all greatly help the potential subsequent optimization of robot elements and their geometry, as well as the parameters of the behavioral mathematical model. The concurrent review of both models (robot architecture and behavior) would facilitate our evaluation of the robot system.

The applications of the ADAMS program is of great importance and help to the authors here, because using of the ADAMS Control interfaces makes it possible to create complex architecture trajectory algorithm (depend on the observed pipeline fitting) and their usage in MATLAB Simulink program to create control algorithm.

The authors hope that this approach, which was previously based solely on the mathematical models and simulation, would be a good initial step toward developing the robot system described.

4 Presentation of Robot CAD Model

To present the CAD model developed using Solid Works, we should first briefly address the robot's architecture, mostly described in an article by Osman and Kovačić, 2017 [3] and herein modified.

The pipeline inspection robot observed consists of two main sections: the driving section and the driven section. The driving section contains an electric motor supplied by a power cable, which drives the transmission (planetary gearbox) that transmits torque against the casing wall, which results in rotational motion which is also transmitted to the driven section. A power cable is attached to the driving section to send system management information. Three legs are mounted on the driven section casing wall, each consisting of two couplings interconnected by rotational joints. Unlike the previously proposed principle where the leg length, i.e. the turning angle between the leg joints is adjusted using a hydraulic cylinder, we set actuators on the lower leg joint, which are based on the electromechanical motion principle. At the end of the leg is a passive wheel made of rubber which is able to rotate around its own axis, but also around a vertical axis using its rotational joint. This ensures that, while moving through the pipeline, the robot's wheel will be able to assume a position being the most favorable one for rotational motion and that the best torque will be achieved. The legs in the driving section are under a 120° angle in relation to their axes. At the end of each leg is a sensor that reads the pressure force against the interior pipeline wall, thus controlling the required force in the actuator. This also acts on the actuator which provides additionally required pressure force against the interior pipeline wall. The driving section is connected with the driven section by a shaft whose casing also has three legs mounted on it. The principle is quite similar as that used for the driving section's legs, except that they have a pair of 4 rubber wheels at the end of each leg which have, on the levers of each pair (see detail A in Figure 1) and mutually, a spiral spring installed that always provides minimum pressure and contact with the surface (pipeline wall). The wheels are connected with the leg joint by a rotational joint. We selected the double-wheel pair because we thought it would be easier for the mechanism to adapt to changes in pipeline curvature and achieve satisfactory traction, while avoiding excessive friction force that would be a restrictive factor in running through the pipeline. There is an option of tilting the driven section in three directions using the spherical joint and groove in the driving section of the robot. This allows the robot to pass any knees, narrowing and widening sections and T pieces in the pipeline. The leg axes in the driven section are under a 60° angle in relation to the leg axis in the driving section to provide for better stability of the device. Each force sensor on each leg allows autonomous control of the leg coupling tilt angle, thus balancing the system while the robot moves through curved sections of the pipeline with an inclination. This also acts on the linear actuator which provides additionally required

force against the pipeline wall. The mass balancing is thus improved. A CCD camera is mounted at the end of the driven section.

Based on the robot architecture described, we presented the robot's CAD model made using the Solid Works software (see Figure), including specifically identified elements on detail A on same picture.

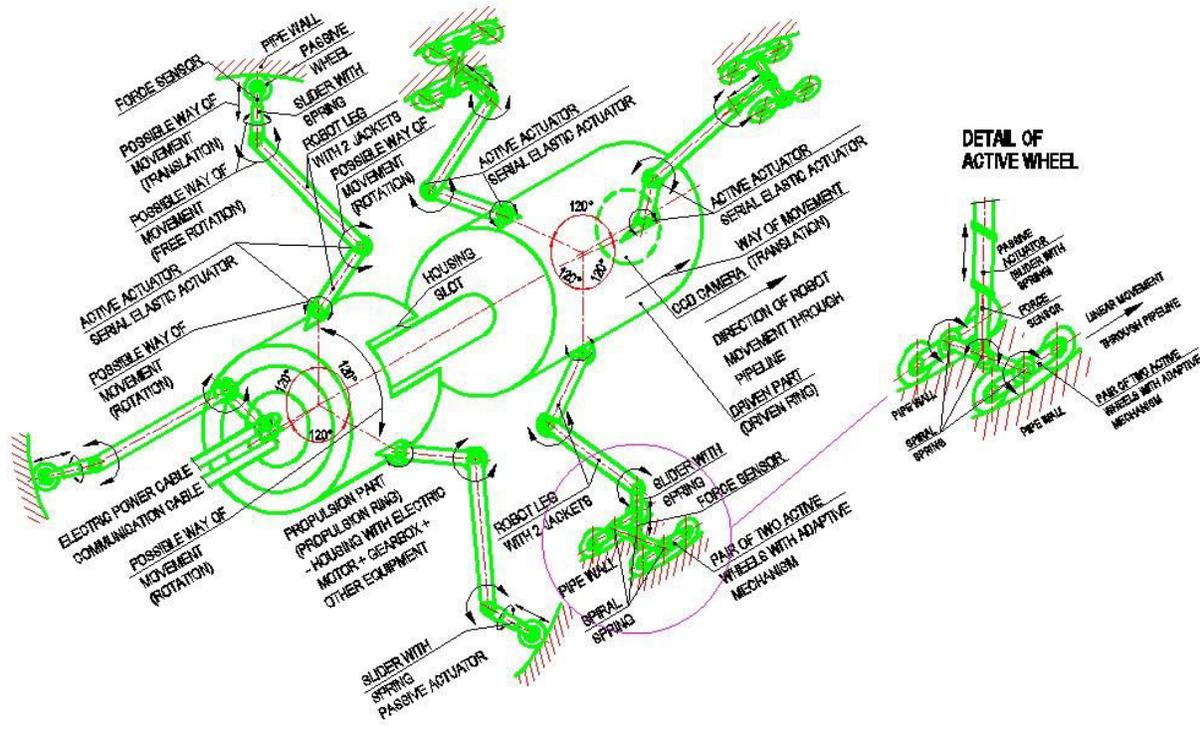


Fig. 1: Robot CAD model with description and details

When dimensioning the robot, certain limitations posed by the observed pipeline configuration in the observed fittings should be taken into account. The dimensions of the robot itself, the diameters of the cylindrical pipeline part, the lengths of both cylindrical parts of the driving and driven sections' casings and the length of each robot leg should be determined according to the inlet diameter of the pipeline for which the robot concerned will be designed, the curvature radius of the pipeline elbows 90° and the T-piece 45° length. This CAD model (presented on Figure 1) for the robot was elaborated and created by observing all of the above values.

5 Mathematical Models of Pipeline Fittings

In this chapter, the authors wanted to present mathematical models of typical pipeline fittings (elbow 90°, narrowing/widening, and T-piece 45°), which are also considered in this paper and are used in the following chapters as the basis for defining the pipeline inspection robot's motion. Firstly, each of the abovementioned pipeline fittings will be described mathematically and then this geometry will be attempted to be linked to the robot geometry which should result in mathematical models of kinematic equations to describe the robot's motion through them. The pipeline fittings so conceived will later be used to run simulations.

5.1 Mathematical model of pipeline fitting – elbow 90°

As mentioned above, the first typical pipeline component to be used to develop the relevant mathematical model is an elbow 90°. As presented in Figure 2a, the pipeline has a central diameter of $R=1.5D$ and has its inlet diameter (D_u) and its outlet diameter (D_v) specified. An assumption we will introduce is that the center of the

coordinate system is located at the center of the observed elbow. This is why the elbow geometry mathematical model may be defined using the following expression in a spherical coordinate system:

$$S(\phi, \lambda) = \begin{bmatrix} (R+0,5D\cos(\phi)) \cos(\lambda) \\ (R+0,5D\cos(\phi)) \sin(\lambda) \\ 0,5D\cos(\phi) \end{bmatrix} \quad (1)$$

where ϕ denotes the position of entering point A into elbow on the inlet pipeline wall from the x-axis, while λ denotes the angle traveled by point A for a particular trajectory. The trajectory (R) is the assumed distance of the robot's center of gravity will travel by running through the pipeline elbow. The trajectory (R) does not precisely match the elbow center and there is a certain deviation between them, identified as Δd in the shown Figure. As presented, it depends on the present position of the robot in the pipeline elbow space.

To determine the velocity of the wheels while moving through the observed pipeline fitting (see Figure 2b), we will identify the robot wheel contact points as points P, Q and R on the driving section, and points P₁, Q₁ and R₁ on the driven part of the robot. The respective velocities at such points may be determined on the basis of the typical relations in similar triangles as presented through the following expressions:

$$|v_P| : |v_Q| : |v_R| = R_P : R_Q : R_R \quad (2)$$

expressed in details

$$|v_P| : |v_Q| : |v_R| = 1,5D - 0,5D\cos(\psi_c) : 1,5D - 0,5D\cos(\psi_c - 120^\circ) : 1,5D - 0,5D\cos(\psi_c + 120^\circ) \quad (3)$$

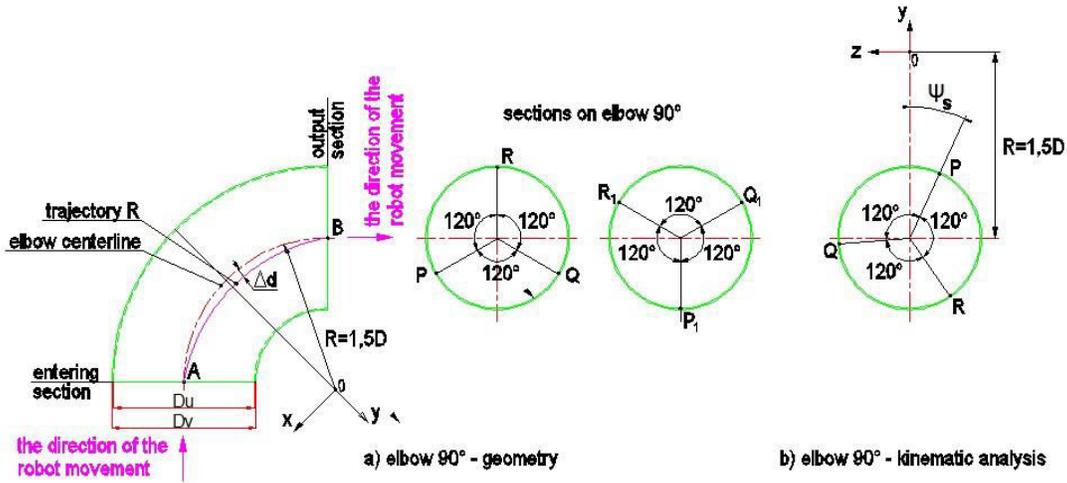


Fig. 2: Geometry for mathematical model of pipeline fitting elbow 90°

5.2 Mathematical model of pipeline fitting – narrowing / widening fitting

The mathematical model for the second typical pipeline fitting (narrowing / widening) is somewhat simpler. Figure 3a presents a pipeline widening, including the dimensions ahead of the widening, which also has its inlet and outlet diameters identified as D_u and D_v , respectively (on entering and outlet section). Analogously, the narrowing fitting also has its dimensions identified as inlet diameter (D_u) and outlet diameter (D_v) (on entering and outlet section). The widening angle between these two pipeline fittings is identified as α . This is followed by a mathematical model for the pipeline expansion geometry, which may be defined in a cylindrical coordinate system. The trajectory (R) is the assumed distance the robot's center of gravity will travel by running through the pipeline elbow. In relation to this pipeline fitting, it matches the center of the pipeline expansion and there is no deviation between them as was the case with the 90° pipeline elbow.

To determine the velocities of wheel movement through this pipeline fitting (widening), similar as in the previous model (see Figure 3b), we will identify the robot wheel contact points as points P, Q and R on the

driving section, and points P_1 , Q_1 and R_1 on the driven part of the robot. The velocities at the above points are defined through the following expressions [3]:

$$v_R = \dot{r}_p = d/dt(L(t) + r_w) \tag{4}$$

$$v_\varphi = r_p \dot{\varphi} = (L(t) + r_w) \dot{\varphi} \tag{5}$$

$$v_x = \dot{x}(t) \tag{6}$$

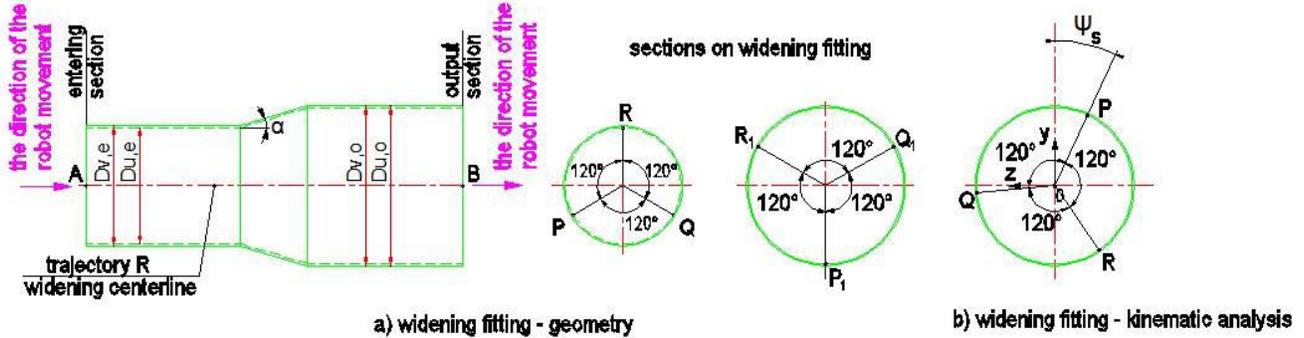


Fig. 3: Geometry for mathematical model of pipeline fitting narrowing / widening

Robot's motion through a narrowing pipeline fitting could be defined in a similar way, provided that it is ensured that the robot starts from a pipeline with a greater diameter toward a pipeline with a smaller diameter. The resulting spatial geometry would apply in this case, and so would the robot motion equations, i.e. its kinematic model.

5.3 Mathematical model of pipeline fitting – T-piece 45°

Describing a mathematical model for the motion through a typical T-piece 45° is much more difficult than it was in the preceding two cases. This is due to the geometry of the T-piece 45°, which cannot be described as a closed-form equation and requires certain assumptions to be established, depending on the direction of robot's motion through it. What is interesting for observation purposes as part of this research is to observe the robot motion (turning) from a T-piece 45° into the main pipe.

This is why a geometric analysis could be conducted in a so-called “intuitive way”. As presented in Figure 4, we selected typical A-A, B-B, C-C and D-D cross-sections. As seen in Figure 4b, the observed curved surfaces of the pipeline fitting are very difficult to describe geometrically in certain indicated cross-sections, so we decided not to derive a mathematical model or its kinematic mathematical models for the robot trajectory for this pipeline fitting.

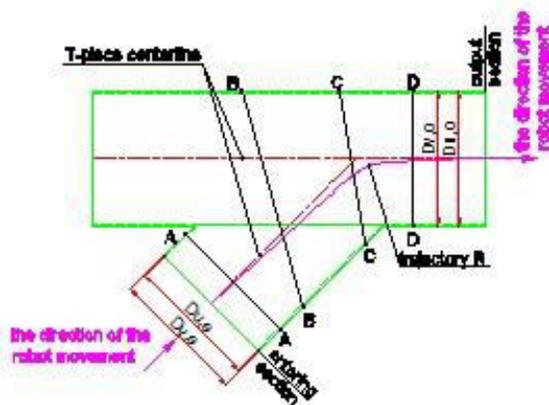


Fig. 4: Geometry for mathematical model of pipeline fitting T-piece 45°

This decision well confirmed the authors' assumptions due to the approach selected for this research. Namely, creating a CAD model with kinematic joints (using Solid Works software) and conducting a kinematic and dynamic analysis using ADAMS View software and using its ADAMS Controls interface will allow us to overcome the above described problem concerning the geometry of the observed space, where our use of ADAMS software will allow us to create a robot system block (with kinematic and dynamic models), which incorporates the spatial geometry (robot trajectory) in each of the typical pipeline fittings observed (elbow 90°, expansion/narrowing, T-piece 45°). In case cases it is possible to develop the mathematical model by analytic methods. On the other hand in certain cases were present a certain degree of system complexity, approximation will not be a good way to get a mathematical model. So simulation is there recommended as an easy way to test the system and get some results which can help in further analysis of observed system. Trajectory planning may be the biggest problem here, because due to some assumptions, this can lead us to large deviations in the results.

6 Description of the control algorithm

Control algorithm of in-pipe inspection robot is based on so-called hybrid compliance control system, including its passive and active parts [18]. At joint between leg jackets and at joint between housing (on driving and driven robot part) and upper leg jacket is mounted active actuator (serial elastic actuator [19]) as active part. Lower jacket of each robot leg also contains passive actuator (passive part), which is represented with cylindrical spring on link between slider and lower jacket. Role of active actuators is to rotate each jacket with the purpose to maintain a certain angle between them and between upper jacket and robot. With these angles is get determined certain adding value of force between wheels and interior wall of pipeline. On each robot leg have been installed force sensor, which detect contact force with the surface (interior pipeline wall).

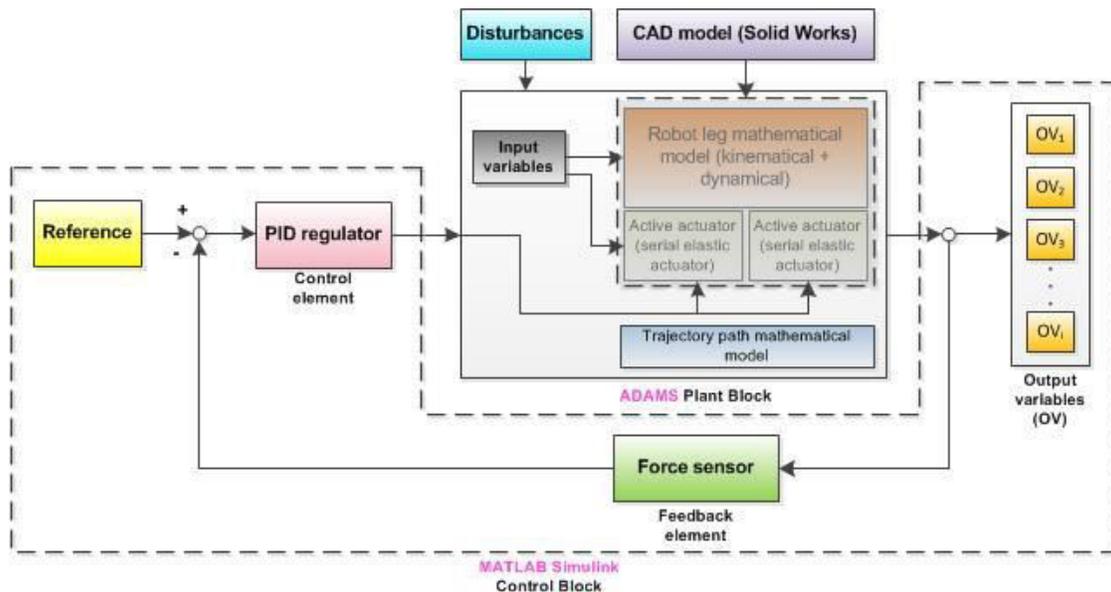


Fig. 5: Block diagram of hybrid compliance control algorithm (for one robot leg)

As can be seen from given block diagram of hybrid compliance control (represent control system for one robot leg) (Figure 5.), diagram consist of two main parts. The first main part is robot plant block, created in program ADAMS Controls, and through this interface it is connected with MATLAB Simulink program, where is created second main part, control block. Robot plant block includes mathematical model of robot (kinematical and dynamic model) included actuators (active and passive parts - fully defined with the set of compliance parameters) with incorporated trajectory path mathematical model. Through the software MATLAB Simulink,

block diagram is supplemented with control parts: PID regulator, force sensor, reference variables and output variables.

7 Co-operation in ADAMS and MATLAB Simulink program

As already mentioned in this paper, we propose an approach that links the three software products –Solid Works, ADAMS and MATLAB Simulink – for the purpose of creating both the robot architecture and its behavioral model. Using the software, we designed CAD models for the respective robot components, subassemblies and assemblies. The robot’s CAD model including its defined kinematic links is imported to the MSC ADAMS View simulation software where it is used to create a CAD/CAE model for a complex mechanical system including all required properties, and kinematic links to all parameters for further kinematic and dynamic analysis. By using the interface within that software (ADAMS/Control), MSC ADAMS and the toolbox within MATLAB Simulink are connected, i.e. data is exchanged between them. In this case, it is output based on the derived robot motion equations and MATLAB Simulink is used to create a system control block diagram. Data is exchanged in the kinematic and dynamic estimation process between the virtual prototype and the system control software, where MSC ADAMS solves the mechanical system equations, while MATLAB Simulink solves the control system equations. The entire data exchange process is presented in the flowchart diagram in Figure 6.

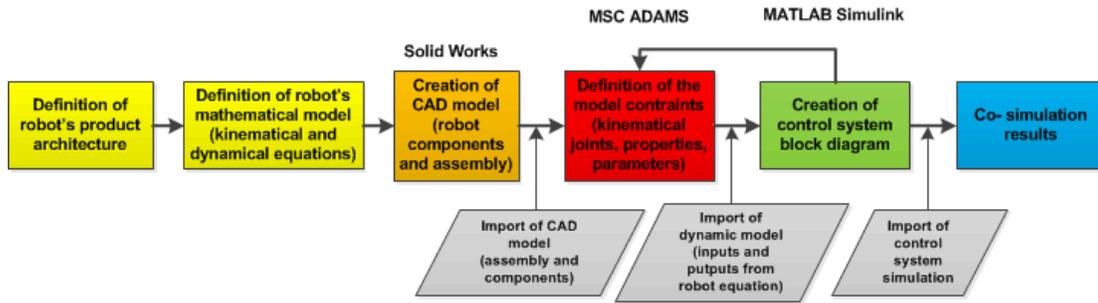


Fig. 6: Flowchart diagram of data exchange between the computer programs Solid Works, MSC ADAMS and MATLAB Simulink

The input variables for the multi-body model of the observed robot should be specified:

- speed of electro motor rotation n_{EM} ,
- speed of DC active actuator on first leg jacket on robot driving part rotation n_{11i} ,
- speed of DC active actuator on second leg jacket on robot driving part rotation n_{21i} ,
- speed of DC active actuator on first leg jacket on robot driven part rotation n_{12i} ,
- speed of DC active actuator on second leg jacket on robot driven part rotation n_{22i} .

The robot model’s output variables, observed as the results of the simulation, should also be specified: The variables into/from the robot are defined as state space variables.

- angle between first leg jacket and housing on robot driving part α_1 ,
- angle between first leg jacket and housing on robot driven part α_2 ,
- angle between first leg jacket and second leg jacket on robot driving part β_1 ,
- angle between first leg jacket and second leg jacket on robot driven part β_2 ,
- velocity of robot driving part v_1 ,
- velocity of robot driven part v_2 ,
- acceleration of robot driving part a_1 ,
- acceleration of robot driven part a_2 ,
- force on passive wheel on driving part F_1 ,
- force on active wheels on driven part F_2 .

8 Discussion on control algorithm and simulation

A brief review and discussion may be provided on control algorithm and simulation process based on the input parameters and the selected pipeline materials, as well as pipeline fittings. It should be noted that the simulation was carried out on two quite often used pipe materials like steel and PVC. The results obtained show that the robot's design and its control algorithm basically provide for the robot's motion through an elbow 90°, i.e. through a pipeline widening and narrowing. Problems arise when the robot is to run through a T-piece 45° because certain aspects are not envisaged by the control algorithm. Namely, the control algorithm does not implement a robot braking option to be used while the robot is approaching a particular pipeline fitting or an option of adjusting the robot legs in such case. As this paper presents robot's motion through a T-piece 45°, future research should also include its motion through a 90° T-piece 90°. However, this requires improvement of the robot control algorithm presented in this research (see Chapter 6).

9 Conclusions and directions of future research

The authors' idea was to present in this article an extension of their research into the behavior of a pipeline inspection robot in typical pipeline sections (such as knees, T pieces, and narrowing and widening sections). The authors believe that, by the concurrent use and combination of the architecture model and the behavioral model would facilitate their evaluation of the robot system. This primarily refers to the possibility of detecting errors in the architecture of the system and its behavioral model (pipeline mathematical models and control model), the potential optimization of robot system elements and their geometry, as well as the behavioral mathematical model parameters.

Based on the concept proposed and described in these authors' previous paper and certain modifications, a detailed design of the robot was provided and its 3D model using Solid Works. This was used to make a simulation using ADAMS and MATLAB Simulink. We also developed and presented mathematical models for the typical pipeline sections (subject to certain assumptions and approximations), as well as a control model based on controlling the force of robot's contact against the pipeline interior wall, i.e. a so-called robot pliability management hybrid system.

In the course of development and generation of the mathematical models, the author encountered some unforeseen restrictions, including in the simulation of the robot's movement using said software, and these are addressed in the description of the results discussion.

The authors believe this research provided them with good feedback about the robot's behavior considering the restrictions they found while conducting such simulations.

As already mentioned, it is imperative to make a pipeline inspection robot prototype and conduct experimental research to confirm and expand the available information about the robot's behavior while moving through typical pipeline branches. This may be proposed as one of the future steps of research.

Further research should also be focused on developing an expended control model based on controlling the force of robot's contact against the interior pipeline wall.

References

- [1] S. Roh and H. Ryeol Choi, "Differential-Drive In-Pipe Robot for Moving Inside Urban Gas Pipelines", *IEEE Transactions on Robotics*, Volume 21, Issue 1, pp. 1-17, 2005.
- [2] A. Kakogawal, T. Nishimura and S. Ma, "Development of a Screw Drive In-pipe Robot for Passing through Bent and Branch Pipes", in *Proceedings of 44th International Symposium on Robotics (ISR)*, October 24-26, Seoul, South Korea, 2013.

- [3] K. Osman and Z. Kovačić, “Development of Structure and Behavioral Model for Screw Driving In-pipe Inspection Robot based on Adaptive Mechanism on Legs”, in *Proceedings of ECCOMAS Thematic Conference on Multibody Dynamics*, pp. 619-626, June 19 - 22, Prague, Czech Republic, 2017.
- [4] ... “ADAMS Tutorial Kit for Mechanical Engineering Courses”, *MSC Software*, 2014.
- [5] ... “MATLAB Simulink Tutorial”, *MathWorks*, 2012.
- [6] L. Ángel, M. P. Pérez, C. Díaz-Quintero and C. Mendoza, “ADAMS/MATLAB CO-SIMULATION: Dynamic Systems Analysis and Control Tool”, *Applied Mechanics and Materials*, Vol. 232, pp. 527-531, Trans Tech Publications, 2012.
- [7] S. Roh, D. W. Kim, J.-S. Lee, H. Moon, and H. R. Choi, “Modularized In-pipe Robot Capable of Selective Navigation Inside of Pipelines”, in *Proceedings of 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1724-1729, September 22-26, Nice, France, 2008.
- [8] C. Cirebea, M. O. Tatar and V. Maties, “The Model and Simulation of A Mini Robot with Active Structure Adaptable to the Pipe Diameter”, *The Archive of Mechanical Engineering*, Vol. LVII, No. 4, pp. 383-391, 2010.
- [9] T. Nishimura, A. Kakogawa and S. Ma, “Pathway Selection Mechanism of a Screw Drive In-pipe Robot in T-branches”, in *Proceedings of 8th IEEE International Conference on Automation Science and Engineering*, pp. 612-617, August 20-24, Seoul, Korea, 2012.
- [10] Y. K. Kang, J. wan Park, and H. S. Yang, “Analytical Approach of the In-Pipe Robot on Branched Pipe Navigation and Its Solution”, *International Journal of Mechanical and Mechatronics Engineering*, World Academy of Science, Engineering and Technology, Vol. 7, No. 5, pp. 907-911, 2013.
- [11] M. Ciszewski, M. Waclawski, T. Buratowski, M. Giergiel and K. Kurc, “Design, Modelling and Laboratory Testing of a Pipe Inspection Robot”, *The Archive of Mechanical Engineering*, Vol. LXII, No. 3, pp. 395-407, 2015.
- [12] M. Ciszewski, L. Mitka, T. Buratowski and M. Giergiel, “Modeling and Simulation of a Tracked Mobile Inspection Robot in MATLAB and V-REP Software”, *Journal of Automation, Mobile Robotics & Intelligent Systems*, Vol. 11, No. 2, pp. 5-11, 2017.
- [13] T. Brezina, Z. Hadas and J. Vetiska, “Using of Co-simulation ADAMS-SIMULINK for Development of Mechatronic Systems”, in *Proceedings of 14th International Symposium MECHATRONIKA*, June 1-3, Trencianske Teplice, Slovakia, 2011.
- [14] H. Zhongling, X. Dongsheng, L. Guangsheng and J. Changzhi, “Study on Co-Simulation Technology Based on ADAMS and MATLAB”, in *Proceedings of International Symposium on Material, Energy and Environment Engineering (ISM3E 2015)*, pp. 595-598, November 28 – 29, Changsha, China, 2015.
- [15] J.-S. Gao, B.-T. Wang, M.-X. Li, „Kinematics Simulation of a Hybrid Leg Structure of a Novel Quadruped Robot”, in *Proceedings of 2016 International Conference on Mechanics Design, Manufacturing and Automation (MDM 2016)*, May 14-15, Suzhou, China, 2016.
- [16] S. İlgen, E. Oflaz, E. Gülbahçe and A. Çakan, “Modelling and Control of a Single-Wheel Inverted Pendulum by Using Adams and Matlab”, *International Journal of Applied Mathematics, Electronics and Computers*, pp. 326-328, Volume 4 (special edition), 2016.

- [17] Y.Y. Huang, J. Wang and D. M. Tham, “Kinematics Modelling and ADAMS MATLAB/Simulink Co-Simulation for Automated Aerobridge Docking Process”, in *Proceedings of 2017 3rd International Conference on Control, Automation and Robotics*, pp. 304-309, April 24-26, Nagoya, Japan, 2017.
- [18] E. Koč, A. Mutka, Z. Kovačić, “New Variable Passive Compliant Element Design for Quadruped Adaptation to Stiffness-Varying Terrain”, *International Journal of Advanced Robotic Systems*, Intech, Vol 13, No. 3, pp. 90-116, 2016 (on-line: doi:10.5772/63893)
- [19] Pratt, G. A., Williamson, M. M., “Series elastic actuators”, in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems 'Human Robot Interaction and Cooperative Robots'*, Vol. 1, No. 1524, pp. 399–406, 1995,