



HAL
open science

Dynamic Model of a Bio-Inspired Robot for Piping Inspection

Damien Chablat, Swaminath Venkateswaran, Frédéric Boyer

► **To cite this version:**

Damien Chablat, Swaminath Venkateswaran, Frédéric Boyer. Dynamic Model of a Bio-Inspired Robot for Piping Inspection. Vigen Arakelian, Philippe Wenger. ROMANSY 22 – Robot Design, Dynamics and Control, 584, Springer, Cham, pp.42-51, 2018, CISM International Centre for Mechanical Sciences (Courses and Lectures), 978-3-319-78962-0. 10.1007/978-3-319-78963-7_7. hal-01807189

HAL Id: hal-01807189

<https://hal.science/hal-01807189>

Submitted on 19 Jun 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Dynamic Model of a Bio-Inspired Robot for Piping Inspection

Damien Chablat¹(✉), Swaminath Venkateswaran², and Frédéric Boyer³

¹ CNRS, Laboratoire des Sciences du Numérique de Nantes, UMR CNRS 6004,
1 rue de la Noë, 44321 Nantes, France

damien.chablat@cnrs.fr

² Ecole Centrale de Nantes, Laboratoire des Sciences du Numérique de Nantes,
UMR CNRS 6004, 1 rue de la Noë, 44321 Nantes, France

³ IMT Atlantique, Laboratoire des Sciences du Numérique de Nantes,
UMR CNRS 6004, 4 rue Alfred Kastler La Chantrerie, 44307 Nantes, France

Abstract. Piping inspection robots are of great importance in industries such as nuclear, sewage and chemical where the internal diameters of the pipeline are significantly smaller. Mechanisms having closed loops can be used in such areas as they generate contact forces and deployable structures. With the help of a bio-inspired mechanism, a piping inspection robot is presented which mimics the motion of a caterpillar. The robot is composed of three modules: a central module for elongation and two other modules on the front and rear for clamping. A slot-slider mechanism is chosen for the legs of the robot. Using industrial components such as DC motors, servo-controllers, ball screws and fasteners, the entire robotic system was realized in CATIA software and a prototype was made at the Laboratoire des Sciences du Numérique de Nantes (LS2N). In this article, we present the forces induced on the motors under locomotion using a dynamic analysis. With the help of the recursive Newton-Euler algorithm, the torques generated on the motor under locomotion have been identified which ensures the stability of the system while moving inside pipes.

Keywords: Piping inspection robot · Bio-inspired mechanism
Dynamic analysis · Newton-Euler algorithm

1 Introduction

Pipeline installations are of great importance in industries such as sewer, chemical and nuclear. Maintenance of these facilities requires regular inspections and repairs. The context of the installations varies in terms of topology (diameters, complexity), environment with chemical risks (gas, deposits, corrosion) and radiations (gamma, beta). The inspection of such pipelines is thus restricted for human beings thereby necessitating the need for an industrial robot. A robot inside a pipeline is subject to various problems such as: (i) locomotion of the system, (ii) positioning of the robot, (iii) inspection of the pipeline and (iv) perform

mechanical tasks (welding, cleaning etc.). In order to simplify the robot design, there are methods to facilitate the choice of the robot's different elements, such as the paw mechanism for managing the contact forces between the robot and the environment. We can distinguish two types of robot family according to their locomotion namely mechanical and bio-inspired systems. A distinction between the two categories was proposed by Kassim et al. [1]. A bio-inspired mechanical system that mimics the motion of a caterpillar has been presented by Henry¹ et al. [2]. The robot has two leg mechanisms for contact points with the walls of a pipe and a central system for elongation. The study of forces and torques on the motor were not done in detail which is very essential to understand the robustness of the system under various inclinations and obstacles within the pipeline. Thus, in this article the force analysis on the robot during locomotion using a dynamic model has been presented. The outline of the article is as follows. The locomotion principle as well as the architecture of the bio-inspired robot is presented. Followed by that, the Newton-Euler algorithm for the dynamic analysis and the results of dynamic forces under locomotion are presented. The article then ends with closing conclusions.

2 Locomotion and Architecture of the Robot

The locomotion of the robot is inspired from the motion of a caterpillar. It comprises of three steps: one for elongation and two others for clamping. A classic way to accomplish this would be with the help of pneumatic bellows and electric motors [3,4]. However, electrical motors are used in all three modules for actuation as they serve better inside pipelines having dust particles. Using the actuators and leg mechanisms, the motion of a caterpillar is mimicked in the robot. The architecture of the robot used in the system as well as the rendered model of the robot inside a pipeline are depicted in Figs. 1 and 2. Three identical actuators, one for elongation in the center and two others for clamping in the front and rear are used in the system. At least one pair of legs remains in contact with the walls of the pipe at all instances of the locomotion cycle. A hyper-static posture exists when both the pair of legs are in contact with the walls of the robot. In our case study [2], the pipe diameters ranges from 74 mm to 54 mm. Owing to an offset of 11 mm caused by the actuators used in the system, the target radius to be swept now ranges from 26 mm to 16 mm. With the help of multi-objective optimization and genetic algorithm [5] in MATLAB, a slot-slider mechanism was chosen for the leg mechanisms of the robot among a set of three architectural candidates. The direct and inverse kinematic models (DKP & IKP) (1 and 2) as well as the inverse of the Jacobian (3) serves as the objective functions for the optimization technique. The equations are as follows:

$$P_y = \frac{l_2^2 e + \rho^2 e + \sqrt{l_1^2 l_2^4 + l_1^2 l_2^2 \rho^2}}{l_2^2 + \rho^2} \quad (1)$$

¹ We would like to thank Renaud Henry, Daniel Kanaan and Mathieu Porez for their participation in the study of this robot.

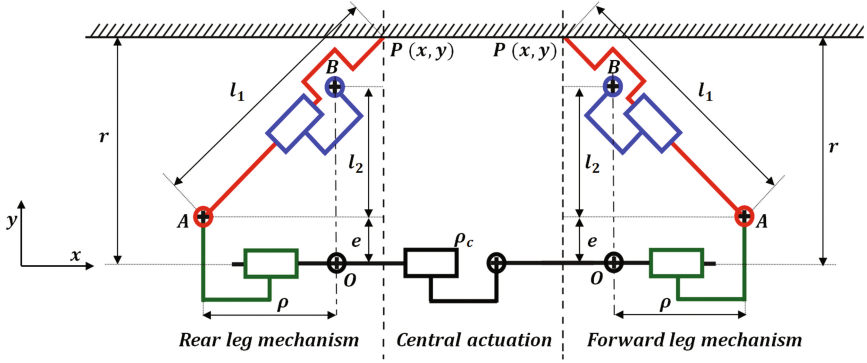


Fig. 1. Cross section of the robot inside a pipeline of radius r

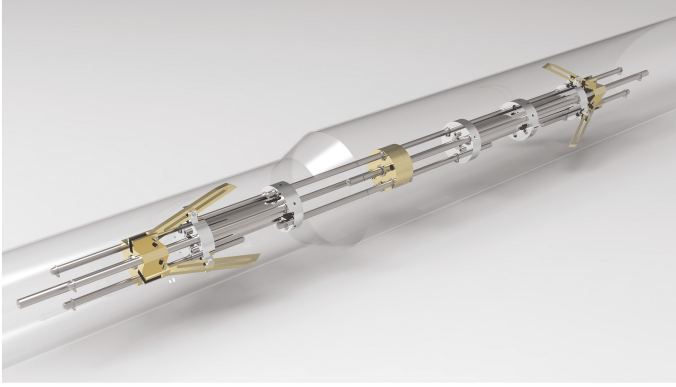


Fig. 2. Rendered model of the robot inside a pipeline using CATIA (We would like to thank Stéphane Jolivet of LS2N for helping in making the prototype and also Benjamin Ioller for software programming.)

$$\rho = \frac{l_2 \sqrt{l_1^2 - e^2 + 2eP_y - P_y^2}}{P_y - e} \quad (2)$$

$$\eta_f = \frac{(\rho^2 + l_2^2)^{3/2}}{l_2 l_1 \rho} = \frac{F_p}{F_a} \quad (3)$$

In Eqs. 1 and 2, P_y signifies the position of the leg that establishes a contact with the walls of the pipeline. In Eq. 3, F_a represents the actuation force of the motor and F_p signifies the contact forces between the legs of the robot and the walls of the pipeline. The dimensions for the leg mechanism used in the robot are: $l_1 = 57$ mm, $l_2 = 7$ mm and $\rho = 8.5$ – 45.5 mm. The six locomotion steps of the robot inside the pipe are depicted in Fig. 3. The three legs of the rear and forward mechanisms have the same dimensions and they ensure non-hyper-static

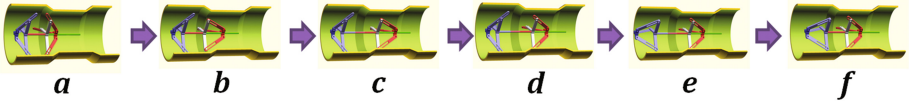


Fig. 3. Six locomotion steps of the robot inside the pipeline

contacts at almost all phases of the locomotion. A Maxon motor GP 16 S (ϕ 16) [6] is used for actuation. Each module has its own motor system. The gear ratio offered by this motor is 1:455. The entire mass of the robotic system is 657 g not taking into account the electronic boards and the power supply. An ESCON 36/3 DC servo-controller (Torque and speed control) [6] is used within the robotic system for an efficient control of the DC motors used for actuation. The torque on the motor can be calculated in two phases: a dynamic algorithm during locomotion and a static algorithm during clamping.

3 Dynamic Modeling

The robot is a multi-body mobile-based system with closed loops. It moves relative to a fixed Galilean frame. A closed loop is a structure composed of two kinematic chains, a passive (not actuated) and an active (actuated) joined together at their ends [9]. We also distinguish the direct dynamic model which is used for estimating the accelerations in the links of the robot with the help of the wrench equations and the inverse dynamic model which is used for estimating the torques and wrench using the accelerations and velocities of the links. In this context, we employ the inverse dynamic model in order to estimate the torques generated on the motor under locomotion. In order to calculate the efforts on the motor under locomotion, two different dynamic models are used and they are represented in Fig. 4.

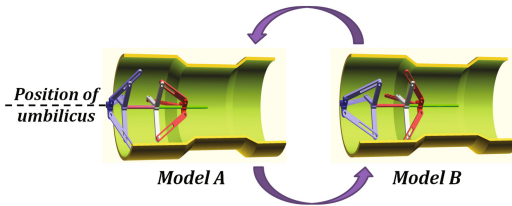


Fig. 4. Change of models in dynamic mode

In Model-A, the reference body is placed on the left clamping module whereas in the Model-B the reference body is placed on the right clamping module. Each model is composed of 29 bodies as represented in Fig. 5 with 9 non-zero masses, 3 active links (red arrows), 18 passive links (blue arrows) and 8 clamping's (E_i).

The entire system appears complex and thus the Denavit-Hartenberg (DH) [8] table is constructed which makes it easier to describe each model. The details of the key body components of Fig. 5 and the material used is provided in Table 1.

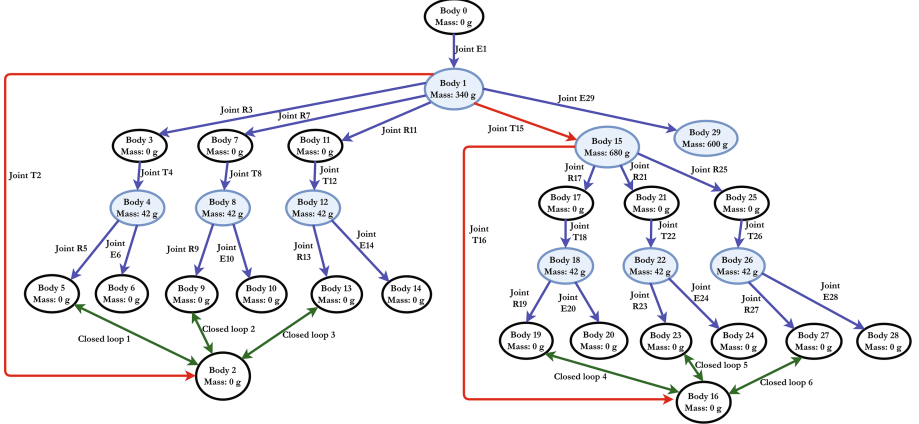


Fig. 5. Dynamic model of the robot for Model-A

3.1 Inverse Dynamics Using the Recursive Newton-Euler Algorithm

Generally, dynamic models are solved by either the Lagrange equations or the Newton-Euler equations. The Lagrange equation is based on the difference between the kinetic and potential energy of the system and the system torque [7] which is given by the equation:

$$\Gamma = A(q)\ddot{q} + H(q, \dot{q}) \quad (4)$$

where A is the inertia matrix of the robot and H represents the Coriolis, centrifuge and gravity torques. As this method is time consuming, Khalil proposed the recursive Newton-Euler (NE) [7], which has proven to be an excellent tool for modeling rigid robots. It involves two recursive algorithms namely: Forward and backward recursions. In the former, the link velocities, accelerations and ultimately the wrench on each links are calculated from link 1 to n . In the backward recursion, the reaction wrenches are calculated from link n to the base of the robot. Also this method provides the joint torques in terms of the joint positions, velocities and accelerations without computing the A and H matrices and the equation is given by:

$$\Gamma = f(q, \dot{q}, \ddot{q}) \quad (5)$$

In order to use the Newton-Euler algorithm, we move from a mobile-based multi-body system with closed loops to a tree-based multi-body system. The homogeneous transformation matrix which defines a frame R_j relative to frame R_i as

Table 1. Description of key body parts represented in Fig. 5

Body No.	Description	Material
Body 1	Left leg actuator	Steel
Body 4	Left leg-1	Bronze
Body 8	Left leg-2	Bronze
Body 12	Left leg-3	Bronze
Body 15	Central & right leg actuator	Steel
Body 18	Right leg-1	Bronze
Body 22	Right leg-2	Bronze
Body 26	Right leg-3	Bronze
Body 29	Umbilicus(Cables)	Copper

a function of six geometric parameters (γ_j , b_j , α_j , d_j , θ_j , r_j) is given by the relation:

$${}^i\mathbb{T}_j = \begin{bmatrix} {}^iR_j & {}^iP_j \\ 0_{1 \times 3} & 1 \end{bmatrix} \quad (6)$$

where iR_j defines the (3×3) rotation matrix and iP_j defines the (3×1) vector that specifying the position of frame j with respect to frame i . The forward NE recursive equations [7] are given by:

$${}^j\dot{\mathbb{V}}_j = {}^j\mathbb{T}_i {}^i\dot{\mathbb{V}}_i + {}^j\gamma_j + \ddot{q}_j {}^j\mathbb{A}_j \quad (7)$$

where ${}^j\mathbb{A}_j$ is a (6×1) columns matrix called as the transposition vector for velocities and accelerations and is given by:

$${}^j\mathbb{A}_j = [0 \ 0 \ \sigma_j \ 0 \ 0 \ \bar{\sigma}_j]^T \quad (8)$$

Here σ_j is a coefficient of the joint type. If the joint is revolute $\sigma_j = 0$ and for prismatic joint $\sigma_j = 1$. Also $\bar{\sigma}_j = 1 - \sigma_j$. ${}^j\mathbb{V}_j$ is a kinematic screw vector of frame j with a size of (6×1) and it contains the linear and angular velocity components. The equation is given by:

$${}^j\mathbb{V}_j = [V_j^T \ \omega_j^T]^T \quad (9)$$

where ${}^j\mathbb{T}_i$ is the screw transformation matrix and it is given by the equation:

$${}^j\mathbb{T}_i = \begin{bmatrix} {}^jR_i & -{}^jR_i {}^i\hat{P}_j \\ 0_{3 \times 3} & {}^jR_i \end{bmatrix} \quad (10)$$

The wrench equation comprises of the external forces and torques and is provided in (11). These forces and torques in the forward recursion is given by (12) and (13).

$${}^j\mathbb{F}_j = \begin{bmatrix} {}^jF_j \\ {}^jM_j \end{bmatrix} \quad (11)$$

$${}^j F_j = M_j {}^j \dot{V}_j + {}^j U_j {}^j M S_j \quad (12)$$

$${}^j M_j = {}^j J_j {}^j \dot{\omega}_j + {}^j \omega_j \times ({}^j J_j {}^j \omega_j) + {}^j M S_j \times {}^j \dot{V}_j \quad (13)$$

Here MS_j and J_j refers to the standard inertial parameters of the link j . The backward recursive equations are calculated with the help of the reaction forces and torques generated on the joints j . The torque induced on the motor is calculated with the help of the reaction forces based on (14) which is given below [7]:

$$\Gamma_j = (\sigma_j^j f_j + \bar{\sigma}_j^j m_j)^{T^j} a_j + I a_j \ddot{q}_j + F_{sj} \text{sign}(\dot{q}_j) + F_{vj} \dot{q}_j \quad (14)$$

Here f_j and m_j are the reaction forces and torques from the links. $I a_j$ is the inertia of the motor. F_{sj} and F_{vj} are the coulomb and viscous friction parameters. The forward and the backward recursive equations using NE algorithm are implemented in MATLAB with the help of which the locomotion sequence of the robot and the forces on the actuators are estimated.

3.2 Results of Simulation During a Locomotion Cycle

With the help of the geometric parameters, links and joints of the robot, using MATLAB the NE recursive algorithm is executed in order to calculate the forces generated on the actuators used in the leg mechanisms as well as the central actuator. The displacement, velocity and acceleration of these actuators are also estimated during the entire locomotion cycle inside a horizontal and vertical pipeline. The diameter of the pipeline used in the prototype as well as the simulation is 74 mm with a diametrical reduction to 54 mm in the middle of the trajectory. The total length of the trajectory (pipeline) taken into account for the simulation is approximately 2.5 m. A fifth-order polynomial interpolation is employed for the motion planning [10]. This interpolation ensures the continuity of the movement in position, velocity and acceleration. The maximum

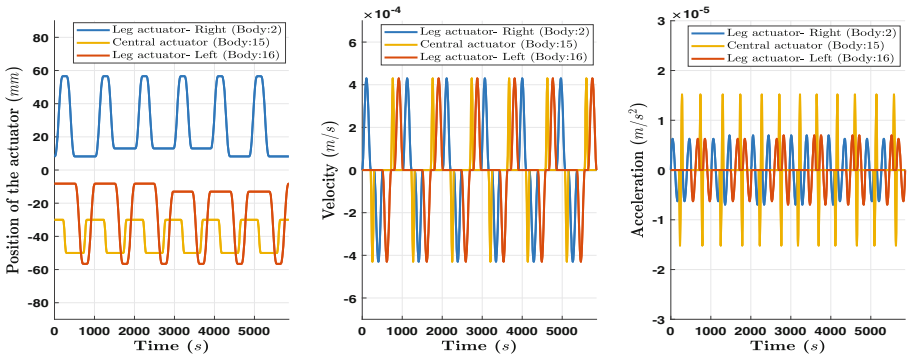


Fig. 6. (From left) Position, Velocity and Acceleration of the right leg actuator, central actuator and the left leg actuator

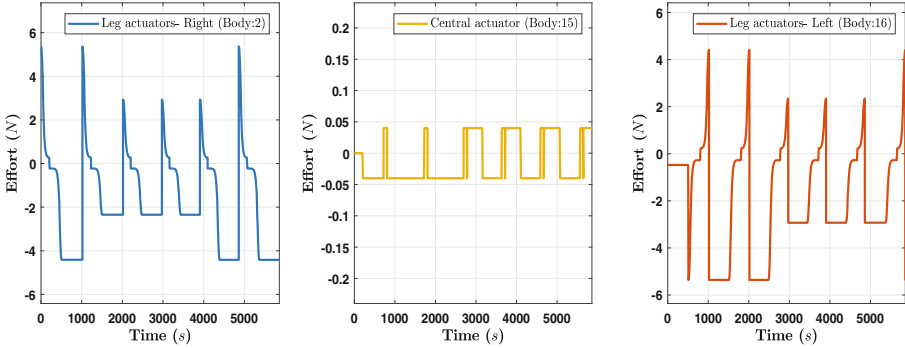


Fig. 7. Forces induced on the actuators during locomotion with horizontal orientation of the pipeline for Model-B

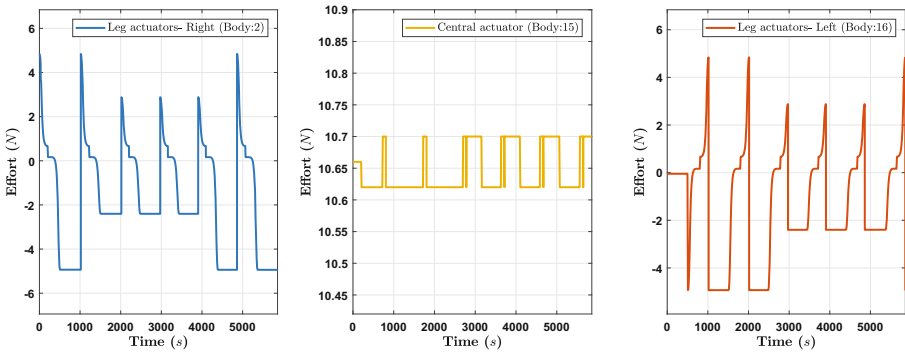


Fig. 8. Forces induced on the actuators during locomotion with vertical orientation of the pipeline for Model-B

velocity of the actuators are 0.00043 m/s in the middle of the locomotion step. The plots of position, velocity and acceleration of the actuators from the start to the end of a simulation cycle is shown in Fig. 6. The diametrical changes inside the pipe could be easily observed on both the leg actuators (Blue and red lines). The extension of the leg actuators are close to 40 mm in the 74 mm diametrical range and changes to around 35 mm for the 54 mm diametrical range. The extension range of the central actuator (Orange line) remains a constant as there are no leg modules attached to this system and it ensures the elongation mechanism of the caterpillar locomotion. The central actuator extends to a maximum distance of 20 mm irrespective of the diameters of the pipeline. The forces induced on the actuators are affected by the orientation of the pipelines. The forces induced on the actuators with a horizontal and vertical orientation of the pipeline for Model-B are shown in Figs. 7 and 8. The forces induced on the actuators are caused by two main factors: Dynamic's due to movement of masses as well as

the umbilicus and the effect of gravity (static masses). The constant lines in the curves represents the effects of gravity. It could be observed that the forces on the leg actuators remain the same during horizontal and vertical orientation of the pipelines. On the other hand, the forces on the central actuator is affected by the orientation of the pipeline as they have no legs attached to them. During horizontal orientation of the pipeline, the forces on the central actuator ranges between 0–0.04 N whereas in the vertical orientation of pipeline the forces ranges between 10.66–10.7 N which indicates the effect of gravity. For the Model-A (not presented here), the forces induced on the central actuator were estimated to be between 8.04–8.1 N. The dynamic effects are caused only by the movement of masses and gravity but there exists no effect from the umbilicus. The forces on the leg actuators in Model-A was exactly the inverse of Model-B and the values remains the same during horizontal and vertical orientation of the pipeline. The clamping forces on the legs can be estimated with the help of static model using the Coulomb's law of friction. This model has not been presented and it helps in estimating the tangential radial and longitudinal forces as well as the normal forces between the legs of the robot and the walls of the pipeline. These forces are essential to estimate the torques induced on the leg actuators during clamping.

4 Conclusions

Thus, a dynamic model using the recursive Newton-Euler algorithm has been presented for a bio-inspired piping inspection robot. It could be observed that during vertical travels, a higher amount of force is induced on the central actuator of the robot when compared to horizontal travel where the force induced on the central motor is closer to zero. The static model for estimating the clamping forces have not been presented. With the velocity of the robot being small (0.00043 m/s), a static analysis using Coulomb's law of friction will be done in the future in order to determine the clamping forces as well as the stability of the system. The impact on the forces induced on the motors caused due to the orientation of the robot inside the pipeline will also be taken into account for further studies. An increase in the speed of the robot will also be proposed by using optimization techniques as well as by changing the motors with smaller gear ratios in order to produce higher velocities.

References

1. Kassim, I., Phee, L., Ng, W.S., Gong, F., Dario, P., Mosse, C.A.: Locomotion techniques for robotic colonoscopy. *Eng. Med. Biol. Mag.* **25**(3), 49–56 (2006)
2. Henry, R., Chablat, D., Porez, M., Boyer, F., Kanaan, D.: MultiObjective design optimization of the leg mechanism for a piping inspection robot. In: *Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Buffalo, United States (2014)

3. Anthierens, C., Ciftci, A., Betemps, M.: Design of an electro pneumatic micro robot for in-pipe inspection. In: International Symposium on Industrial Electronics, Bled, pp. 968–972 (1999)
4. Anthierens, C., Libersa, C., Touaibia, M., Betemps, M., Arsicault, M., Chaillet, N.: Micro robots dedicated to small diameter canalization exploration. In: International Conference on Intelligent Robots and Systems, Takamatsu, pp. 480-485 (2000)
5. Ur-Rehman, R., Caro, S., Chablat, D., Wenger, P.: Multiobjective path placement optimization of parallel kinematics machines based on energy consumption, shaking forces and maximum actuators torques: application to the orthoglide. *Mech. Mach. Theory* **45**(8), 1125–1141 (2010)
6. Maxon motor's, Program 2017/18. High precision Drives and Systems. Information, pp. 363–427 (2017). <http://epaper.maxonmotor.com/#1>
7. Khalil, W.: Dynamic modeling of robots using recursive Newton-Euler techniques. In: 7th International Conference on Informatics in Control, Automation and Robotics, Portugal (2010)
8. Khalil, W., Kleinfinger, J.F.: A new geometric notation for open and closed-loop robots. In: Proceedings of IEEE International Conference on Robotics and Automation, San Francisco, pp. 1174–1180 (1986)
9. Boyer, F., Ali, S.: Recursive inverse dynamics of mobile multibody systems with joints and wheels. *IEEE Trans. Robot.* **27**(2), 215–228 (2011)
10. Khalil, W., Dombre, E.: Modeling, Identification and Control of Robots. Hermes Penton Ltd. (2002)