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Stability Analysis Approach in Development of In-pipe Inspection Robot

Krešimir Osman[1], Trpimir Alajbeg[1]

[1]Department of Electrical Engineering
Zagreb University of Applied Sciences
Konavoska 2, 10000, Croatia
[kresimir.osman, trpimir.alajbeg]@tvz.hr

EXTENDED ABSTRACT

1 Introduction

Due to the complexity of piping systems with all their components, as they consist of several different pipe elements (straight pipe sections, bends, tees, constrictions or extensions), equipment capable of inspecting the inner wall on longer sections of the pipeline is needed. Numerous types of robots capable of moving inside the pipeline have been developed for the maintenance and inspection of the pipelines with the aim of preventing various types of damage, cracks, material aging and corrosion phenomena. Since the complexity of the pipeline and, in particular, the pipe elements determine the particular conditions for the robot's movement through the pipeline, the development of the structures of such types of robots, as well as the algorithms for their control, is one of the most attractive areas of service robotics at present. Inspired precisely by this, the authors started their research and published two scientific papers so far. The first paper [1] presents the beginnings of the research on the development of pipeline inspection robots, as well as the model of the structure of the gas pipeline inspection robot and the derived behavioral model (mathematical model). The movement of the robot is based on the main movement mechanism, which is based on a screw with an adaptive mechanism of the pressure of its wheels on the wall of the pipeline. Continuing the research, mathematical models of typical pipeline elements, such as the bend, tee, constriction or widening, were presented in the work [2], and on this basis kinematic and dynamic equations of the robot motion through these elements were derived. In addition, the model of the robot control system, called the hybrid compliance control system [3], including its passive and active parts, was shown. In this work, the approach of linking three computer programs - Solid Works, MSC ADAMS and MATLAB Simulink - was proposed to create architectural models of the robot and models of its behavior. The Solid Works computer program was used to create a CAD model of the robot's individual components, subassemblies, and assemblies. The CAD model of the robot with its defined kinematic connections is imported into the computer simulation program MSC ADAMS View, where on its basis a CAD /CAE model of a mechanically complex system with all necessary properties and kinematic connections is created with all parameters for further kinematic and dynamic analysis. Through the interface within this ADAMS /Control program, the computer programs MSC ADAMS and the toolbox within MATLAB Simulink are connected, i.e. there is an exchange of data between them. In this case, this is the output data according to the derived equations of motion of the robot, and MATLAB Simulink additionally creates a block diagram of the system control. During the kinematic and dynamic calculation process, data is exchanged between the virtual prototype and the system control software, where the computer software MSC ADAMS solves the equations of the mechanical system, while MATLAB Simulink solves the equations of the control system.

2 Problem Description

Since most of the research conducted and published so far, as well as the research carried out in the paper [2], has been done by computer simulations as well as by experiments on horizontal pipeline sections, the authors had the idea to study in this paper the behavior of the pipeline testing robot during its movement through pipeline sections as well as their pipe elements, but on a terrain that is either subsiding or rising along a slope. Accordingly, it would be important to investigate the stability of the robot, i.e., whether the proposed robot architecture presented in papers [1] and [2] can meet the requirements of moving the robot through such a piping configuration. Accordingly, tests of the robot's stability were performed in this work, in which differences in the robot's behavior were observed when moving through an ascending pipeline, as well as when moving through descending pipeline sections with respect to the angle between the center of the observed pipeline and the horizontal terrain. Comparisons of robot stability for the robot architecture shown in papers [1] and [2] (with at least 3 robot legs) and for the robot with the number of robot legs increased to 4 were given, as well as the effects on robot behavior and stability.

3 The Applied Methods and the Obtained Results

The idea was to model the behavior of the pipeline testing robot as a system of rigid bodies, housings, and its limbs connected by joints. However, the difference between such a mathematical model and the "classical" model of robotic manipulators lies in its basis. Here, as in the case of walking robots, the so-called floating base is used [4], since its configuration depends not only on the position of the joints, but also on the configuration of the base in space. According to the laws of center-of-mass mechanics, the model of the floating base is also considered as a rigid body whose configuration has six degrees of freedom of motion. Accurate determination of the configuration of the base requires data on its position and orientation. In addition, its kinematic and dynamic equations are modeled. Spatial vectors are used to describe the equations, i.e. 6-dimensional vectors [4] that summarize the linear and angular components of motion and forces of rigid bodies. Their use allows a more compact record of the equations of motion of rigid bodies and, consequently, a more compact record of the algorithms for the dynamics of rigid bodies. Two vector spaces are defined here: M^6 - spatial motion vectors which describe the motion of the rigid body (speed, acceleration, infinitesimal shift, etc.), and F^6 - spatial force vectors which describe the effect of force on the rigid body (force, amount of motion, impulse, etc.). For the description of the kinematic robot model [4, 5], the following data is required: N_B - number of members, N_J - number of joints, jtype (i) - type of the i joint (rotational, translational, spherical, etc.), $\lambda(i)$ - the predecessor of the i joint (for the rigid bodies chain $\lambda(i) = i - 1$), X_T - relative position of the robot system and I - a list of space tensors of robot inertia in the coordinate system of that body.

The dynamic robot model equation [4, 5] can be shown as follows

$$\mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{B}(\mathbf{q}, \dot{\mathbf{q}}) = \boldsymbol{\tau} \tag{1}$$

where: $\boldsymbol{H}$ -robot inertia tensor, $\boldsymbol{B}$ -bias force (the effect of gravitational forces, centrifugal, Coriolis and external forces), τ - vector of the generalized forces of the robot joints. For robots with a floating base, the robot dynamics equation (1) can be transformed and shown as follows

$$\begin{bmatrix} \mathbf{H_{00}} & \mathbf{H_{0*}} \\ \mathbf{H_{*}} & \mathbf{H_{**}} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}_{\mathbf{0}} \\ \ddot{\mathbf{q}}_{*} \end{bmatrix} + \begin{bmatrix} \mathbf{B_0} \\ \mathbf{B_*} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\tau}_{\mathbf{0}} \\ \boldsymbol{\tau}_{*} \end{bmatrix} \tag{2}$$

where values with index 0 relate to a virtual unactuated joint with 6 degrees of freedom of motion, and the values with index * relate to the joints of the robot.

Control algorithm of in-pipe inspection robot is based on so-called hybrid compliance control system, including its passive and active parts [3]. 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 [3]) as active part.

The method used for testing the system stability [6] for certain robot system architectures was the so-called direct method or the second Lyapunov method. Depending on the nature of Lyapunov's function, conclusions can be inferred on the stability of the equilibrium state of the system (stable state and asymptotic stability, and unstable state). To observe stability, we need to observe a linear unactuated system, invariant in regards to time. By observing the Lyapunov's matrix equation

$$\mathbf{A}^{\boldsymbol{T}}\mathbf{P} + \mathbf{PA} = -\mathbf{Q} \tag{3}$$

The stability test is carried out by first selecting the symmetric matrix Q, which must be positively designated (usually selected to be a positive matrix). Then the symmetrical matrix P is calculated from the equation (3). If it is positive, then the system is globally asymptotically stable in the sense of Lyapunov [6, 7].

4 Conclusions and Directions of Future Research

This analysis served the authors as a tool for a comprehensive consideration of the overall behavior of the robotic system, as well as for the creation of the mathematical model for a possible optimization of the elements and their geometry, as well as the parameters of the mathematical behavior model. As mentioned above, it is essential to produce a prototype pipeline inspection robot and to conduct experimental studies to confirm and extend the available information on the robot's behavior when moving through typical pipeline branches. The authors suggest several directions for future research. The first is the creation of a robot prototype that will allow the performance of an experimental analysis and its comparison with the obtained simulation results. In addition, a further development of the control method is proposed, based on an algorithm to control the contact force, as well as the active and the changeable passive part.

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