ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2008. No. 1(81)
ELEKTRONIKA IR ELEKTROTECHNIKA

AUTOMATION, ROBOTICS
T125
AUTOMATIZAVIMAS, ROBOTECHNIKA

Simulation and Code Generation for a Parallel Kinematic Manipulator with three Degrees of Freedom

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Introduction

The students' assignment was to model and simulate a parallel kinematic structure using MATLAB/Simulink plus appropriate toolboxes. The results had to be verified with a real-world model also built by the project group, thus placing emphasis on the relevance of modelling and simulation in modern mechatronics. The software needed to run the real-world model had to be real-time. However, automatic software generation was used to relieve the students of the need to write real-time software, which would have distracted them from the original goal. The parallel kinematic structure chosen was a simple table that compensates for movements of the base platform, to which it is linked by linear guides.

To keep the upper platform horizontal and at a defined height, two degrees of freedom in orientation and one degree of freedom in Cartesian position are necessary. The 3DOF parallel manipulator with RPS joint structure (rotational – spherical – prismatic) proposed in [1] fulfills these requirements. Using a manipulator with SPR joint structure [1] would increase the working space, but the calculation of the inverse kinematics would need more calculation power.

This platform will be used as teaching aid in mechatronics studies as an example for calculating the inverse kinematics of a simple parallel kinematic manipulator. A commercial application can be found in keeping tables, floors or solar panels of a vehicle or vessel in a defined orientation. In contrast to a pure mechanical solution, parameters (damping, target orientation) can be easily modified online.

Inverse Kinematics

The platform has three degrees of freedom which can be verified with Grübler's formula [3]. l represents the total number of rigid bodies of the mechanism, including the base; n is the total number of joints and d_i the number of degrees of freedom of joint i. The mobility m of the platform is

$$m = 6 \cdot (l - n - 1) + \sum_{i=1}^{n} d_i = 3. \tag{1}$$

In the following the height of the centre (Cartesian z-coordinate) of the upper platform and two angles describing the normal vector of the upper platform are chosen as independent variables.

A base coordinate frame *{G}* is fixed on the center of the base platform. The links are connected to the base platform by means of pin joints at the fixed positions ${}^{B}P_i$ spanning an equilateral triangle. An upper platform coordinate frame *{H}* is fixed on the center of the upper platform.

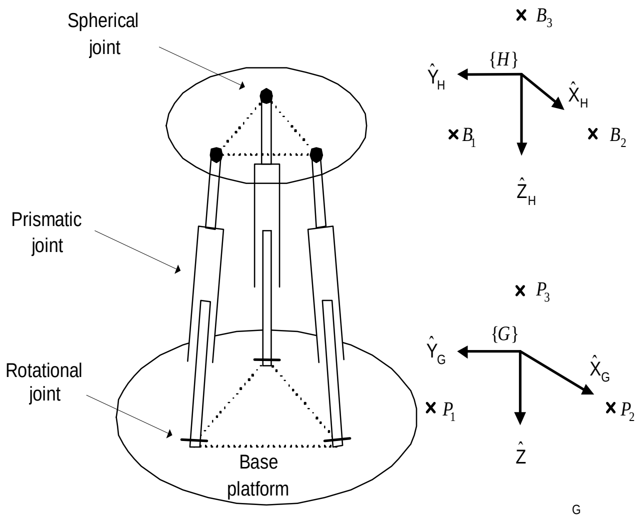

Fig. 1. Schematic representation and coordinate systems of the 3-RPS manipulator

The links are connected to the upper platform by means of ball joints at the moving positions ${}^{H}B_i$ (see Fig. 1). The coordinate frame *{H}* with respect to the base coordinate frame *{G}* can be described using ZYZ-Euler angles by the homogeneous transformation matrix ${}^{G}_{H}T$ [4]:

$$
{}^{G}_{H}T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & x_c \\ r_{21} & r_{22} & r_{23} & y_c \\ r_{31} & r_{23} & r_{33} & z_c \\ 0 & 0 & 0 & 1 \end{bmatrix} =
$$

$$
\begin{bmatrix} c_\alpha c_\beta c_\gamma - s_\alpha s_\gamma & -c_\alpha c_\beta s_\gamma - s_\alpha s_\gamma & c_\alpha s_\beta & x_c \\ c_\alpha c_\beta c_\gamma - s_\alpha s_\gamma & -c_\alpha c_\beta s_\gamma - s_\alpha s_\gamma & s_\alpha s_\beta & y_c \\ -s_\alpha c_\gamma & s_\beta s_\gamma & c_\beta & z_c \\ 0 & 0 & 0 & 1 \end{bmatrix}, \qquad (2)
$$

where s_χ is short for $\sin(\chi)$, c_χ for $\cos(\chi)$.

The column vector $[x_c \quad y_c \quad z_c]^T$ denotes the translation from the center point of the base to the center point of the upper platform. The position of the ball joints B_i with respect to the base frame $\{G\}$ can be expressed as

$$
{}^{G}B_i = {}^{G}_{H}T \cdot {}^{H}B_i . \qquad (3)
$$

The inverse kinematic equation (eq. 4) defines the actuating length l_i by determining the Euclidian distance from ${}^{G}B_i$ to ${}^{G}P_i$.

$$
l_i = norm\left({}^{G}B_i - {}^{G}P_i\right) = norm\left({}^{G}_{H}T \cdot {}^{H}B_i - {}^{G}P_i\right). \qquad (4)
$$

The homogeneous transformation matrix ${}^{G}_{H}T$ describes the pose of the platform and the following two paragraphs show, how the parameters of ${}^{G}_{H}T$ can be determined.

Orientation

The normal vector of the plane defined by the upper platform sufficiently describes the orientation of the platform and it is identical to the z-axis of the coordinate system of the upper platform $\hat{Z}_H$ with respect to the base frame $\{G\}$:

$$
{}^{G}\hat{Z}_H = \begin{bmatrix} r_{13} \\ r_{23} \\ r_{33} \end{bmatrix}. \qquad (5)
$$

Orthogonal mounted accelerator sensors based on Micro-Electro-Mechanical Systems technology (MEMS) are used to measure the vector of acceleration of gravity. The sensor values u_i correspond to the directional cosines of the gravity vector r_{1i}:

$$
norm\left(\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}\right) = \begin{bmatrix} r_{13} \\ r_{23} \\ r_{33} \end{bmatrix} = \begin{bmatrix} c_\alpha s_\beta \\ s_\alpha s_\beta \\ c_\beta \end{bmatrix}. \qquad (6)
$$

Defining $0 < \beta < \frac{\pi}{2}$ the ZYZ-Euler angles α and β can be calculated as

$$
\alpha = \operatorname{atan2}(r_{23}, r_{13}), \qquad (7)
$$

$$
\beta = \operatorname{acos}(r_{33}). \qquad (8)
$$

N.B. For $-\frac{\pi}{2} < \beta < 0$ the $\sin(\beta) < 0$ and so $\alpha = \operatorname{atan2}(-r_{23}, -r_{13})$ and $\beta = -\operatorname{acos}(r_{33})$.

The remaining dependent parameter γ is calculated using constraint equations imposed by the pin joints [1] as

$$
\gamma = -\alpha . \qquad (9)
$$

Position

The position of the moving platform is described by the column vector $[x_c \quad y_c \quad z_c]^T$. The Cartesian coordinate z_c is defined by the set point of the height of the table. The dependant variables x_c and y_c can be determined using constraint equations imposed by the pin joints [1] as

$$
x_c = -\frac{r}{2}(1 - \cos(\beta)) \cdot \cos(2\alpha), \qquad (10)
$$

$$
y_c = -\frac{r}{2}(1 - \cos(\beta)) \cdot \sin(2\alpha). \qquad (11)
$$

Simulation

There are several reasons for realizing a model of the platform. Firstly, it is possible to check the functionality of the construction and to determine the working area by simulation. Furthermore, the control program can be developed and tested before the real platform is available. The mechanical construction is performed with the CAD program SolidWorks [5] and the data is exported to SimMechanics [6], a simulation tool for mechanical systems. Using SimMechanics the dynamic behavior of the platform can be tested with a real or simulated control before it is set up. The model of the manipulator respects geometrical constraints, joints and mass distribution. Friction is neglected in this model.

Prototype

The prototype consists of a mechanical construction (see Fig. 2) and a PC (Pentium IV, 2Ghz) equipped with data acquisition card (Meilhaus PCI2600i) which captures the data of the accelerator sensors (Analog Devices ADXL150) and outputs the pulses for the drive amplifiers (SMC LC6D) for the linear stepper motors (SMC LXS). The PC runs Windows XP with a real-time kernel (Real-time Windows Target [6]) extension. This enables the system to run Simulink models in real time.

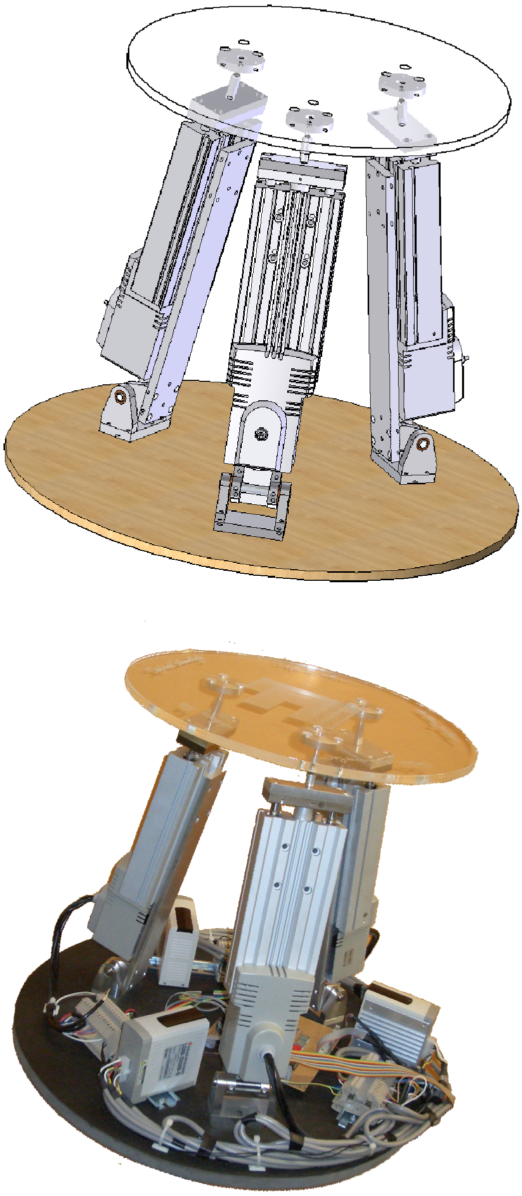

Fig. 2. CAD-model and photograph of the 3-RPS manipulator

For measuring the static earth acceleration vector two low-cost dual-axis micromechanical sensors are mounted on the base in alignment with the base system *{G}*. Various methods for compensating errors in gain, offset, linearity and non-orthogonality are described in the literature[7-9].

The control program calculates the length of the prismatic axis corresponding to eq. 4 from the signals of the accelerator sensors with a sample time of 39.68 ms. The sub-program which creates the pulses for the stepper drives is executed with a sample time of 330 μs. The program is tested using the SimMechanics model of the platform and is used without modification for the real world task. The Real-Time Workshop Toolbox [6] translates Simulink models into C-Code for specific target platforms. The PC can thus be replaced by an embedded system and the program for the embedded system can be generated directly from the Simulink model of the control program.

The linear drives used have a stroke of 100mm and a lead of 30μm per pulse. The maximum start-up frequency is 1400 pulses per second and the maximum continuous frequency is 3000 pulses per second (no load). This is taken into account in the Simulink-program which controls the drive.

Experimental Results

The manipulator is tested by manually changing the orientation of the base platform. The setpoint values $l_{i,setpoint}$ and actual values $l_{i,actual}$ representing the lengths of the linear drives are depicted in Fig. 3. The setpoint values are calculated from the signals of the MEMS sensors and as it can be seen in Fig. 3 the values are remarkably noisy, which is caused by the vibrations of the stepping motors.

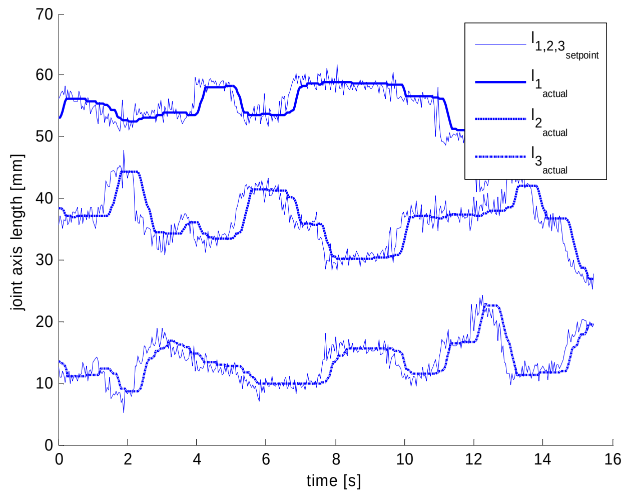

Fig. 3. Actuating lengths of the prismatic joint axes (setpoint and actual values)

The noise is filtered by the low-pass characteristic of the motors and furthermore a hysteresis of +/-50 pulses is applied to the setpoint value which causes a systematic error of +/-1.5 mm in actual axis lengths. The experiments on the target platform have shown that the stepping motors induce a considerable amount of noise to the sensors. A matter of fact that could not show up in simulations because of unavoidable simplifications made during the modeling process.

Conclusion and Future Possibilities

The goal of this project was to use a simple parallel kinematic structure to show the potential of modeling and simulation in mechatronics with modern software tools. A prototype had to be built, not to serve as a kind of rapid-development platform, but rather to test the concept. However, even in this case MATLAB/Simulink is of great help, because code-generating software is available, thus removing the tedious task of writing real-time software. In this way the students could concentrate on their task and eventually build a real-world model from scratch: They selected the sensors, designed the drives, and built the model completely in the short time available. The project group thus demonstrated the value of modeling and simulation in the teaching of mechatronics, and we will use these didactic methods even more in future.

Further steps will be the modeling of the accelerator sensors and the simulation of the movement of the base platform.

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Submitted for publication 2007 10 27

R. Amann, F. Geiger. Simulation and Code Generation for a Parallel Kinematic Manipulator with three Degrees of Freedom // Electronics and Electrical Engineering. – Kaunas: Technologija, 2007. – No. 1(81). – P. 27–30.

A mechatronic design for a table which is maintained in a horizontal position by actively controlling the length of three prismatic joints is presented. The inclination is measured by means of accelerator sensors based on Micro-Electro-Mechanical Systems technology (MEMS) and the prismatic joints are driven by servo drives. The effectiveness of the design is experimentally validated on a prototype. The paper shows how computer simulation and automated code generation can be used to design and implement mechatronic systems, and demonstrates the benefits of these technologies. Ill. 3, bibl. 9 (in Lithuanian; summaries in English, Russian, Lithuanian).

Р. Аман, Ф. Гейгер. Имитация и автоматизированное кодирование параллельного кинематического манипулятора с тремя степенями свободы // Электроника и электротехника. – Каунас: Технология, 2007. – № 1(81). – С. 27–30.

Представлен проект для проектирования стола, который поддерживается в горизонтальном положении, активно управляя длиной трех призматических соединений. Склонность стола измеряется посредством датчиков акселератора, основанных на микроэлектромеханической технологии систем (MEMS), а контроль ведется через призматическое соединение трех сервомоторов. Эффективность проекта экспериментально утверждена на опытном образце. Работа показывает, как компьютерное моделирование и автоматизированное кодирование могут использоваться для проектирования и осуществления электромеханических систем. Ил. 3, библ. 9 (на литовском языке; рефераты на английском, русском и литовском яз.).

R. Amann, F. Geiger. Lygiagrečios kinematikos trijų laisvės laipsnių manipuliatoriaus modeliavimas ir kodo generavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 1(81). – P. 27–30.

Pateikiamas horizontalia kryptimi manipuliuojamo staliuko projektavimas ir valdymas naudojant tris prizmines jungtis. Staliuko padėties pasikeitimas matuojamas akselerometru, o padėtis nustatoma naudojant tris servopavaras. Suprojektuotas įrenginys eksperimentiškai lyginamas su pagamintu prototipu. Darbe daroma išvada, kad šiuolaikinių mechatroninių sistemų projektavimas pasitelkiant kodo generavimą turi daug pranašumų. Il. 3, bibl. 9 (lietuvių kalba; santraukos anglų, rusų, ir lietuvių k.).