Kinematics Analysis, Design, and Control of an Isoglide3 Parallel Robot (IG3PR)

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***Abstract*-The paper presents a novel structure of the Isoglide3 Parallel Robot (IG3PR), as an effective robotic device with three degrees of freedom manipulation. The IG3PR manipulator offers the characteristics, advantageous relative to the other parallel manipulators (light weight construction), while on the other hand alleviates some of the traditional weaknesses of parallel manipulators, (extensive use of spherical joints and coupling of the platform orientation and position). The presented IG3PR robot employs only revolute (rotary) and prismatic (sliding) joints to achieve the translational motion of the moving platform. The pivotal advantages of the presented parallel manipulator are the following: all of the actuators can be attached directly to the base; closed-form solutions are available for the forward and inverse kinematics; and the moving platform maintains the same orientation throughout the entire workspace. In addition to these comparative improvements, the paper presents an innovative user interface for high-level control of the Isoglide3 parallel robot. The novel IG3PR was verified and tested, and results in MATLAB, Simulink, and SimMechanics were presented.**

Index Terms – kinematics, design, control, simulation, 3 DOF parallel robots.

I. INTRODUCTION

Parallel structures have proved numerous advantages over the conventional machines. In spite of this, there has not been a breakthrough of parallel structures, which could be accredited, particularly from the user's point of view, to the following facts:

1. parallel structures have an unfavorable ratio of the working area vs. the total robot space, and to the
2. small working space.

Many researchers attempted to minimize these disadvantages by optimizing the robot structure [1, 2, 3, 10, 11].

Substantial research has been performed on parallel robots with fewer than six degrees of freedom in order to overcome disadvantages resulting from the coupling of the e position and orientation of the mobile platform, and difficulties related to high cost spherical joints manufacturing. Han Sung Kim and Lung-Wen Tsai [4] presented a parallel manipulator called CPM that employs only revolute and prismatic joints to achieve translational motion of the moving platform. They described its kinematic architecture and discussed the rotary and linear actuation methods.

In case of the rotary actuation, the inverse kinematics provides two solutions per limb, while the forward kinematics results in the eighth-degree polynomial. Furthermore, the rotary actuation results in many singular points within the workspace. On the other hand, in case of the linear actuation, a one-to-one correspondence exists between the input and output displacements of the manipulator.

The 3-DOF parallel robot IG3PR shown in Fig. 1, consists of a moving platform connected to a fixed base by three links. Each link is made up of one prismatic and three revolute joints where all joint axes are parallel to one another.

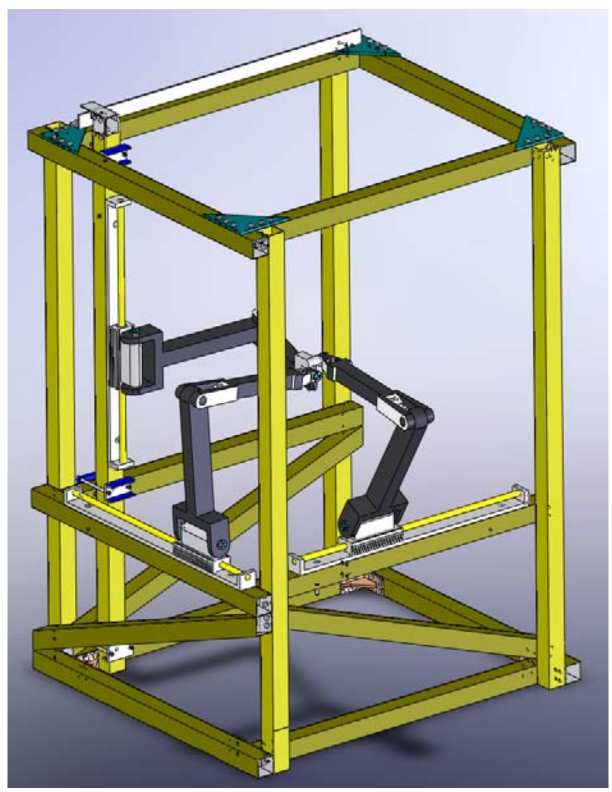

Fig. 1 Assembly drawing of the 3DOF Isoglide3 parallel robot

Section II describes the 3 DOF parallel robots. In this section kinematics analysis of the Isoglide3 parallel robot is provided. The third section introduces the control issues using PID controller. The fourth section presents the experimental test, while the final, fifth section concludes this paper.

II. Kinematics of the 3 DOF Isoglide3 Parallel Robot (IG3PR)

The kinematic structure of the IG3PR, the 3 DOF Isoglide3 parallel robot is shown in Fig. 3. Here, a mobile platform is connected to a fixed base by the three PRRR (Prismatic Revolute Revolute Revolute) links.

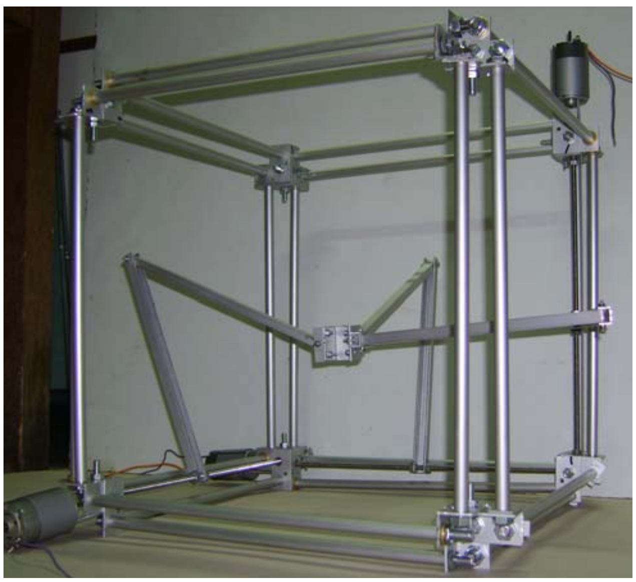

Fig. 2 Isoglide3 parallel robot realized at Dept. of Mechatronics, Technical University of Cluj-Napoca

The origin of the fixed coordinate frame is located at point O, where the reference frame XYZ is attached to the fixed base (Fig. 3.).

The mobile platform is symbolically represented by a square, whose side length 2L is defined by points B_1, B_2, and B_3, and fixed base is defined by three guide rods that are passing through points A_1, A_2, and A_3, respectively.

The three revolute joint axes at the each link are located at points A_i, M_i, and B_i, respectively, and are parallel to the ground connected prismatic joint axis.

Furthermore, the three prismatic joint axes, passing through points A_i, for *i* = 1, 2, 3, are parallel to the X, Y, and Z axes, respectively.

Specifically, the first prismatic joint axis lies on the X-axis; the second prismatic joint axis lies on the Y axis; and the third prismatic joint axis is parallel to the Z axis.

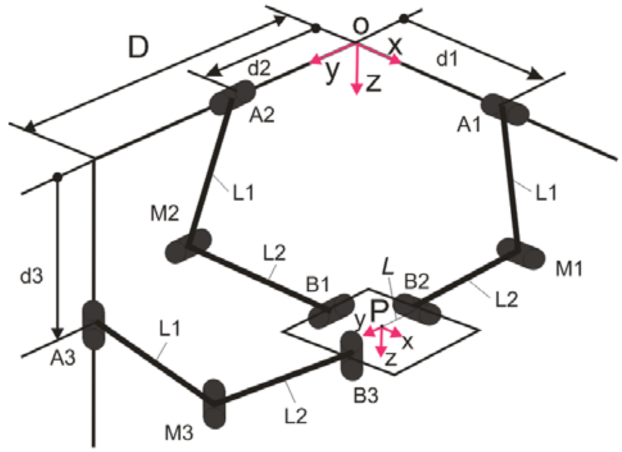

Fig. 3 Kinematic scheme of 3 DOF Isoglide3 parallel robot

Point P represents the center of the moving platform. The link lengths are L_1 and L_2.

The starting point of a prismatic joint is defined by d_{0i} and the sliding distance is defined by d_i - d_{0i}, for *i* = 1, 2, and 3.

A. Kinematics constraints

In this analysis, the position of the end-effector is considered to be known, and is given by the position vector P= [x, y, z], which defines the location of point P at the center of the moving platform in the XYZ coordinate frame.

The inverse kinematics analysis produces a set of two joint angles for each link (θ_{i1} and θ_{i2} for the *i*-th link), that define the possible postures of each link for the given position of the moving platform.

B. The first link

A schematic diagram of the first link of the Isoglide3 parallel robot is sketched in Fig. 4, while the relationships for the first link are written for the position P[x, y, z] in the coordinate frame XYZ.

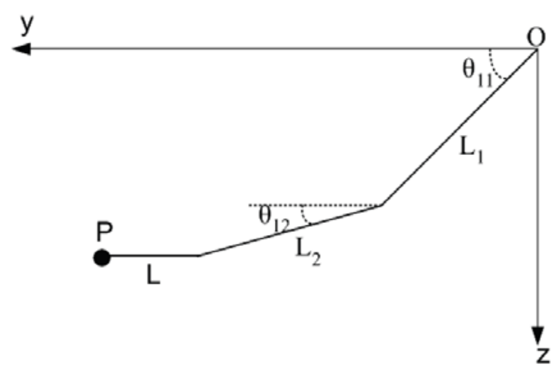

Fig. 4. Description of the joint angles and link lengths for the first link.

$$y = L_1 \cos\theta_{11} + L_2 \cos\theta_{12} + L \qquad (1)$$

$$z = L_1 \sin\theta_{11} + L_2 \sin\theta_{12} \quad (2)$$

$$L_2^2 = \left(y - L_1 \cos\theta_{11} - L\right)^2 + \left(z - L_1 \sin\theta_{11}\right)^2 \quad (3)$$

C. The second link

A schematic diagram of the second link of the Isoglide3 parallel robot is sketched in Fig. 5, and then the relationships for the second link are written for the position P [x, y, z] in the coordinate frame XYZ.

$$z = L_1 \cos\theta_{21} + L_2 \cos\theta_{22} \quad (4)$$

$$x = L_1 \sin\theta_{21} + L_2 \sin\theta_{22} + L \quad (5)$$

$$L_2^2 = \left(z - L_1 \cos\theta_{21}\right)^2 + \left(x - L_1 \sin\theta_{21} - L\right)^2 \quad (6)$$

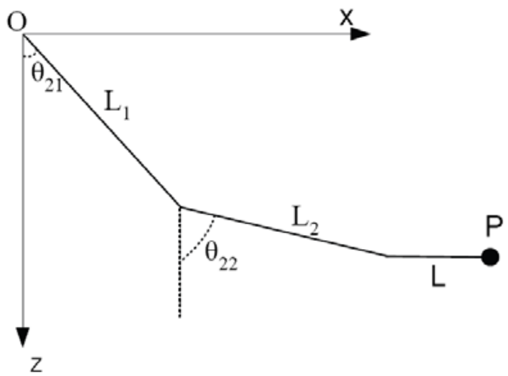

Fig. 5. Description of the joint angles and link for the second link

D. The third link

A schematic diagram of the third link of the Isoglide3 is sketched in Fig. 6, and then the relationships for the third link are written for the position P [x, y, z] in the coordinate frame XYZ.

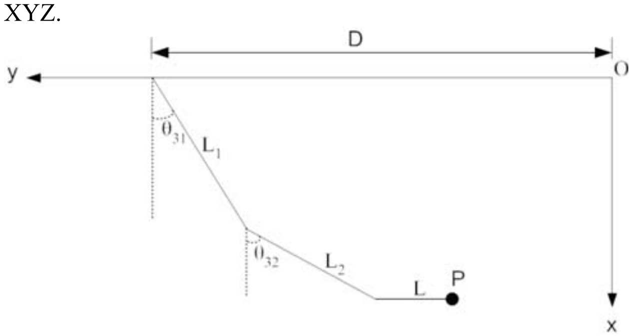

Fig. 6. Description of the joint angles and link lengths for the third link.

$$x = L_1 \cos\theta_{31} + L_2 \cos\theta_{32} \quad (7)$$

$$y = D - L - L_1 \sin\theta_{31} - L_2 \sin\theta_{32} \quad (8)$$

$$L_2^2 = \left(x - L_1 \cos\theta_{31}\right)^2 + \left(y - D + L_1 \sin\theta_{31} + L\right)^2 \quad (9)$$

E. Linear actuation method

As described by Han Sung Kim and Lung-Wen Tsai [4], in case of a linear actuation method, a linear actuator drives the prismatic joint in each link whereas all the other joints are passive. The advantage of this approach is that all of the actuators can be installed on the fixed base. Also, since one-to-one correspondence exists between the end-effector position and the input joint displacements, forward and inverse kinematic analyses is trivial.

Figures 2 & 3 imply that for each link, constraints of that link restrict the movements of point P to the plane that is perpendicular to the prismatic joint axis of the linear actuator in its point Ai.

For example, for the first link, this plane can be visualized as being perpendicular to x axis, intersecting this axis exactly at point A1, and containing points B2, M1, and A1. Consequently, the location of point P is determined by the intersection of three planes. A simple kinematic relation can be written as (10).

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix} \quad (10)$$

For the implementation and resolution of forward and inverse kinematic problems of a parallel robot, a MATLAB environment was chosen. This is where a user friendly graphical user interface was developed, as well.

III. Control of the Isoglide3 Parallel Robot

The control of the parallel robot is implemented using a joint-based control scheme. In such a scheme, the end-effector is positioned by finding the difference between the desired extent of movements and the actual one, expressed in the joint space.

The command of the robot is expressed in Cartesian coordinates of the end-effector. Using the inverse kinematic problem, these coordinates become displacements. These displacements will further become the reference points for the control algorithm.

The control scheme of the robot is presented in Fig. 7.

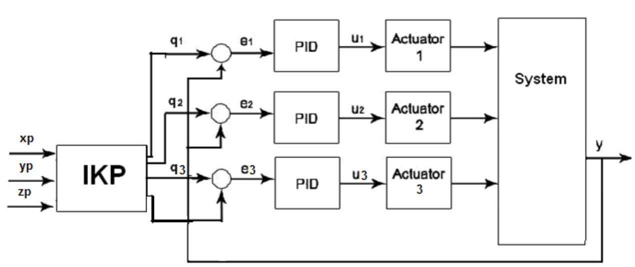

Fig. 7 Control block scheme for Isoglide3 parallel robot

The simulation of running the robot was based on the Simulink module from MATLAB.

MATLAB/Simulink was chosen as a tool that is a widely used for modeling, simulation and testing of dynamical systems.

A model in Simulink is represented graphically by means of a number of interconnected blocks.

The simplest control strategy, which can be taken into account, is view on the robots-manipulators, powered by group of the independent systems (drives - actuators), controlled separately, as a set of single-input / single-output systems. Isoglide3 parallel robot is controlled by means of traditional PID schemes in position/velocity, considering only their kinematics: the reference trajectory of the end-effector is established a priori.

It's planned in the future to apply the use of more sophisticated algorithms, such as *hybrid position-force control (HPFC)* and *impedance control*, which allows fulfilling the requirements of complex and critical tasks, sometimes still performed manually and in general to enhance the performance of the robot.

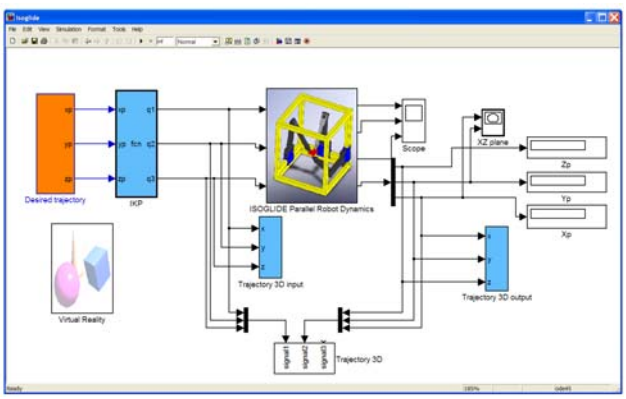

Fig. 8. MATLAB/Simulink model of the Isoglide3 parallel robot

Fig. 8 presents the model of the parallel robot. The actuators and the control algorithm were modeled with Simulink. The dynamic model of the mechanical structure was imported from SolidWorks using SimMechanics from MATLAB/Simulink.

Fig. 9. Generation of SimMechanics model of the Isoglide3 parallel robot

The equations for Inverse Kinematics Problem (IKP) were implemented via a MATLAB *embedded function*, where the inputs were the position and the orientation of the end-effector, while the outputs were the angles for each actuator. At the core of this development is the SimMechanics physical modelling toolbox of Simulink, used to create libraries with integrated "body segment" modules, which are serially connected to create a block diagram representation of the articulated robot mechanics.

SimMechanics was chosen for this task as it offers a suite of interchangeable robotic components. SimMechanics is based on Simulink, and as such, all common options for exporting and plotting data were readily available. In addition, SimMechanics is able to visualize the results without any additional coding (Fig. 11).

Therefore, MATLAB/SimMechanics toolbox was used for an ease of to the design of the rigid body mechanical system connected by joints.

Due to its block diagram based nature, MATLAB/SimMechanics constructs a mechanical system model by connecting some basic model blocks like MATLAB/Simulink routines, and can encompass hierarchical subsystems.

SimMechanics offers the possibility to visualize and animate the robot. The visualization tool can also be used to animate the motion of the system during simulation. The bodies of the robot can be represented as convex hulls (Fig. 14).

These are surfaces of minimum area with convex curvatures that pass through or surround all of the points fixed on a body. The visualization of an entire parallel robot with 3 degrees of freedom was the set of the convex hulls of all its bodies.

A second option was to represent the bodies as equivalent ellipsoids. These are unique ellipsoids centered at the body's center of gravity, with the same principal moments of inertia and principal axes as the body.

Standard Simulink/SimMechanics blocks have been used to create the Isoglide3 robot modules, whose internal structure can be easily modified by the user, and tailored to the requirements of particular applications, should such a need arise.

Furthermore, all the available MATLAB/Simulink add-ins (toolboxes, coding options, etc.) can be used within this framework to implement additional features.

SimMechanics is capable of modeling a large number of DOF and CAD models exported from, for example, SolidWorks can be imported into SimMechanics providing a relatively straightforward solution to simulate complex 3-D multi-body rover designs.

IV. Experimental Test

F. Path tracking performance and visualization

The first tests on the prototype seem to encourage the direction of the research: the chosen control algorithms emphasize the peculiar characteristics of the parallel architecture and, in particular, the good dynamic performance due to the limited moving masses, with a well robot behavior.

For the evaluation of the Isoglide3 parallel robot model performance, a circular trajectory in 3 dimensional space was used, as shown by Figs. 11 & 12.

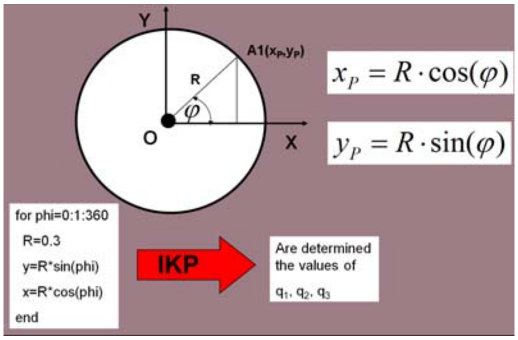

Fig. 10. 2D trajectory generation of circle for the Isoglide3 parallel robot in MATLAB/Simulink

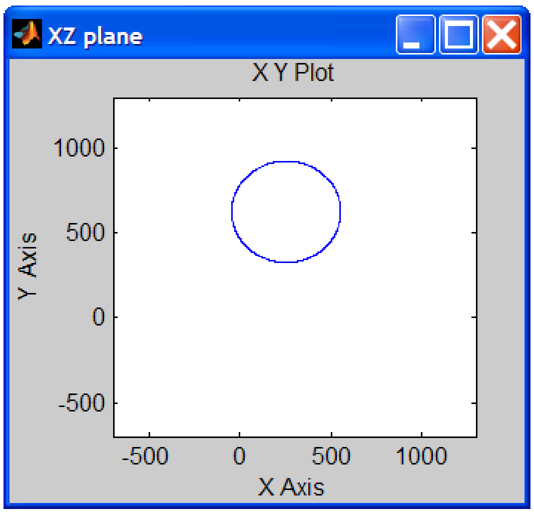

Fig. 11. 2D plot of trajectory of the Isoglide3 parallel robot in MATLAB/Simulink

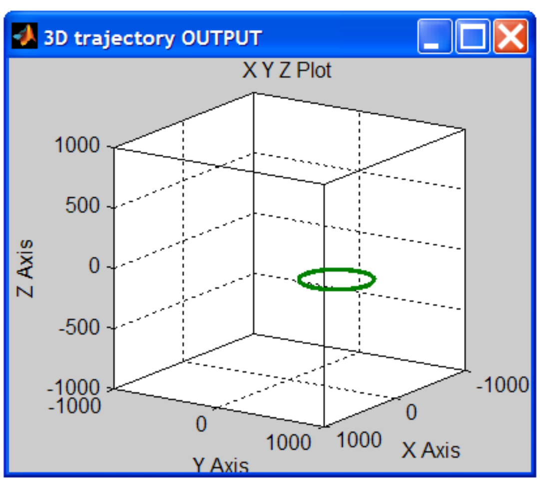

Fig. 12. 3D plot of trajectory of the Isoglide3 parallel robot in MATLAB/Simulink

In order to obtain a circle as trajectory it was given a sine input to the x-axis and cosine input to the y-axis, while keeping 0 to z-axis (Fig. 12). Radius of the circle trajectory is set to 0.3 m.

In Simulink/SimMechanics translational and rotational motions can be simulated in all three dimensions. Simulink/SimMechanics also provides users with a tool to specify bodies and their mass properties, their possible motions, kinematic constraints, coordinate systems and the means of initiating and measuring motions.

In addition, the Physical Modeling environment of SimMechanics tool makes the task much easier.

Moreover, since SimMechanics allows construction of the mechanical models without the user having to derive the associated equations of motion (time-consuming process), the simulation environment can also be used by researchers from fields other than robotics, even with limited mechanical background.

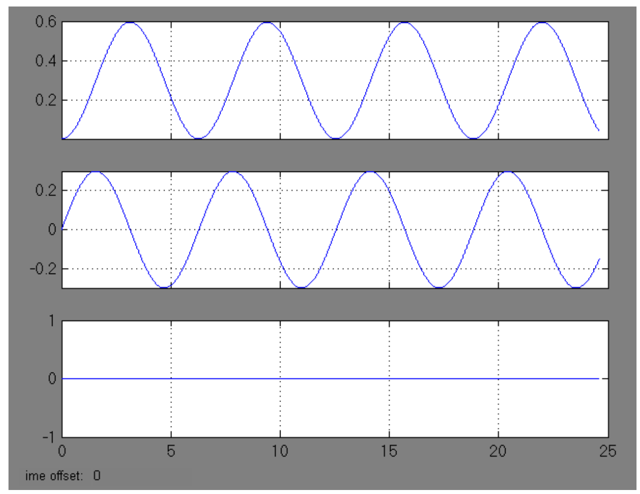

Fig. 13. Input data to generate 3D plot of trajectory of the Isoglide3 parallel robot

Simulations for motion and control have been conducted using the Matlab SimMechanics toolbox.

Software packages such is MATLAB/SimMechanics allow visualizing the motion of mechanical system in 3D virtual space where non-experts and novices can benefit from the proposed visualization tools, as they facilitate the modeling and the interpretation of results.

SimMechanics software also gave the freedom to change the mechanical and mathematical settings used in the simulations.

A main advantage is the flexibility to avoid simulation errors and optimize performance, subject to the fundamental tradeoff between speed and accuracy.

The MATLAB Graphics-based visualization tool is built into SimMechanics software. In the SimMechanics menu of the visualization window, one can choose how the IS3PR parallel robot or any machine bodies are rendered.

In the Machine Display submenu, one can choose Convex Hulls or Ellipsoids. It should be also taken into account that SimMechanics visualization does not have the information about the bodies needed to render their full geometries (see Fig. 14.).

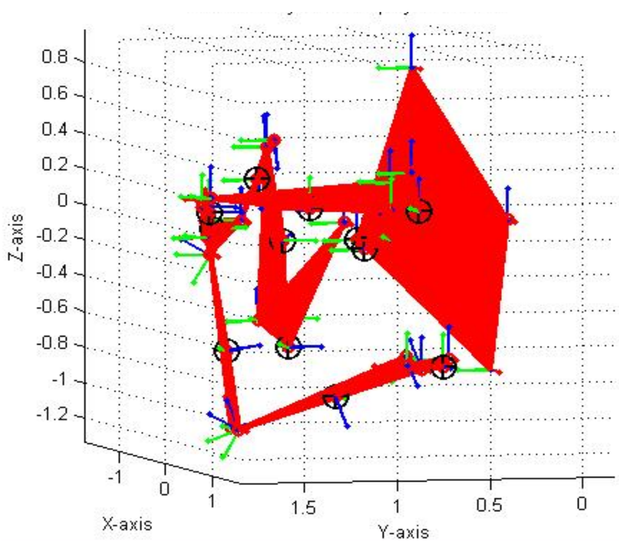

Fig. 14. Physical model of Isoglide3 parallel robot as convex hulls in Matlab/SimMechanics

Related simulation results were presented to illustrate the versatility of these tools and the potential of their use in a variety of other robotic systems.

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CONCLUSIONS

The paper presents an IG3PR, an Isoglide3 Parallel Robot, a new structure of a 3 DOF parallel robot, along with its kinematics analysis and design. It was tested and simulated its design in Matlab environment (Simulink and SimMechanics). The novel interface approach presented in this paper was used as an interactive tool for dynamics system modeling and analysis of an Isoglide3 parallel robot.

The main advantages of this parallel manipulator are that all of the actuators can be attached directly to the base, that closed-form solutions are available for the forward and inverse kinematics, and that the moving platform maintains the same orientation throughout the entire workspace.

By means of SimMechanics we considered robotic system as a block of functional diagrams. Related simulation results are presented to illustrate the versatility of these tools and the potential of their use in a variety of other robotic systems.

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