MODELING AND SIMULATION OF A NEW PARALLEL ROBOT USED IN MINIMALLY INVASIVE SURGERY

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Abstract: Surgery is one of the fields where robots have been introduced due to their positioning accuracy which exceed the human capabilities. Parallel robots offer higher stiffness and smaller mobile mass than serial ones, thus allowing faster and more precise manipulations that fit medical applications. In the paper is presented the modeling and simulation of a new parallel robot, based on an innovative structure, used in minimally invasive surgery. The parallel architecture has been chosen for its superiority in precision, repeatability, stiffness, higher speeds and occupied volume. The robot kinematics, singular position identification and workspace generation are illustrated. Using the developed virtual model of the parallel robot, some simulation tests are presented.

1 INTRODUCTION

Simulation is one of the essential aspects in the robots research field. The industrial trend is to develop simulation systems, which could be helpful for the robot off-line control and for the robot operational workspace generation. Due to the high graphical possibilities and memory capacities, the personal computers offer already the necessary instruments to achieve efficient simulation systems. Within the simulation system, an important role plays the achievement of a virtual robot functional model, which allows its interactive visualization and functional simulation.

The first important application of the simulation systems is during the design process of a new robot structure or a new flexible cell. In both cases it is possible to test the functionality and the restrictions influence without the actual building of the prototype. In this way the costs, the implementation and testing time are considerable reduced.

The second kind of important application of the simulation systems refers to the existent robots that could be better programmed, analyzed and optimized if the research activity is considered.

Within the simulation systems, the visualization of the robot trajectory with collision detection is achieved, offering a safer system especially for the case in which several robots are coupled, situation that requires a more rigorous planning.

The robotized system performance can be tested without any danger for the man or for the robot. The programs generated within the simulation system could be optimized before their practical implementation leading to any damage avoidance due to programming facilities, cost reduction and quality improvement.

Another advantage of the simulation systems consist in their use in the research field. New control algorithms can be created and tested before investments in the necessary hardware devices for the robot control to be made.

To the parallel robots simulation systems are attributed different meanings: numerical simulation for a specific robot function or element in transition; parallel computing for the robot state and transitions definition; the graphical simulation of the robot structure and motion. In some cases the animation is considered as simulation.

Geometric modeling is one of the keystones of CAD systems. It uses mathematical descriptions of geometric elements to facilitate the representation and manipulation of graphical images on a computer display screen. In three-dimensional representations, there are four types of modeling approaches, (Foley et al., 1990) and (Pisla, 2001): Wire frame modelling; Surface modeling; Solid modeling; Hybrid solid modeling.

Simplifying the virtual model enables researchers to apply for the use of different methods (usually starting with the most recommended one) in correspondence with the available time and existing endowment in order to compare the obtained results and refine only the most adequate solution. In practice, the application of simulation techniques is used in two situations: for already made structures to improve their characteristics; for new designed structures to forecast their behaviour before construction.

Lately is considered more the second case, due to the intense development in creating new structures with better dynamics and larger cinematic facilities, or considering the parallel kinematic, a multibody system can be designed to be used like a machine tool or like a robot, therefore the same kinematical structure must respond to different tasks that can be demonstrated with the simulation techniques.

One of the first achieved models in order to achieve the robot simulation is the geometric model. There are many possibilities to create this model also in this case. In respect with the chosen model, different aspects regarding the mechanism properties or actuating methods are emphasized.

The modeling process is oriented to the correlation between the method and the structure in order to point out the influence of the modeling instruments on the structure design.

Considering that the robot performances depend on the adequate combination between the designed structure, the actuating and the control system, the applying of suitable modeling and simulation techniques could improve the robot design and

control through: identification of standardized element behaviour with modular dimensions; identification and visualization of the operational workspace, which is harder to be achieved in the parallel robot case; identification of different parallel robot singularities and their avoiding; trajectory visualization which must be programmed for certain parallel robot tasks; speeds and acceleration visualization in different trajectory points.

Regarding the application of robots for medical applications there are some investigators focused on exploring the capabilities of parallel robots in this field (Ben-Porat, 2000), (Glozman, 2001), (Grace, 1993). AESOP robotic arm, used to guide a tiny camera inside the body, was the first robotic system used in surgery dating from 1993 (Brown University, 2005). It was produced by Computer Motion, which developed several such versions of AESOP until they created Zeus^{TM} Robotic Surgical System with three robotic arms attached on the side of the operating table. A competitor of Computer Motion, Intuitive Surgical, designed another revolutionary equipment, da Vinci^{TM} Surgical System, which became the market competitor of Zeus until 2003 when the two companies merged (Brown University, 2005).

Most of the robots, which assist the surgeons, are serial robots (Brown University, 2005). The serial module generates a large workspace while the parallel module is steadier and offers a high accuracy during the surgical operation. In this case, there are used force control algorithms in order to ensure the safety behavior and the accepted accuracy.

Parallel robots offer a higher stiffness and smaller mobile mass than serial robots, thus they allow faster and more precise manipulations. The problems concerning parallel structures kinematics are usually more complicated than for the serial structures. The drawbacks of serial robots, determined by their structural construction, motivate the research in the field of robotic assisted surgery for a continuous search of task oriented robot architectures that best fit a specific group of medical applications.

The paper is organized as follows: Section 2 is dedicated to modeling techniques; Section 3 deals with kinematic modeling of the new parallel structure designated to minimally invasive surgery; Section 4 presents its workspace modeling, Section 5 presents the developed simulation program for parallel robots with some simulation tests on a studied parallel robot. The conclusions of this work are presented in Section 6.

2 MODELING TECHNIQUES

Bottom-up Modeling Assembly Approach is the modeling technique where component parts are designed and edited in isolation of their usage within some higher level assembly (Pisla, 2004). All assemblies using the component are automatically updated when opened to reflect the geometric edits made at the piece part level. Using the bottom-up approach, characteristic of traditional engineering design practices, designs are built from known components (embodiments) in anticipation of satisfying functional requirements. The bottom-up approach is known to be highly iterative. In the case of large or complex designs, the problem quickly leads to combinatorial explosion, inefficiency in the design process, and difficulties assessing the effectiveness and merits of design alternatives.

Bottom-up design is the traditional method. In bottom-up design, you create parts, insert them into an assembly, and mate them as required by your design. Bottom-up design is the preferred technique when you are using previously constructed, off-the-shelf parts. An advantage of bottom-up design is that because components are designed independently, their relationships and regeneration behavior are simpler than in top-down design. Working bottom-up allows you to focus on the individual parts.

Top-Down Modeling Assembly approach is the modeling technique where component parts can be created and edited while working at the assembly level (Pisla, 2004). Geometric changes made at the assembly level are automatically reflected in the individual component part immediately. In the top-down approach, characteristic of a systems engineering process, design is driven from functional requirements toward solution alternatives. While design solutions using this approach are likely to meet functional requirements, there is no guarantee that solutions are realizable in terms of physical manifestations.

Top-down design is different because you start your work in the assembly. You can use the geometry of one part to help define other parts, or to create machined features that are added only after the parts are assembled. You can start with a layout sketch, define fixed part locations, planes, and so on, then design the parts referencing these definitions. For example, you can insert a part in an assembly, then build a fixture based on this part. Working top-down allows you to reference model geometry, so you can control the dimensions of the fixture by creating geometric relations to the original part. That way, if you change a dimension of the part, the fixture is updated.

Analyzing both techniques characteristics, the bottom-up assembly approach has been chosen for parallel robot modeling due to their advantages.

3 KINEMATIC MODELING OF THE PARAMIS ROBOT

In Figure 1 is presented the kinematic scheme of the new parallel structure – PARAMIS, which can be used for surgical instruments positioning (Plitea, 2007). The structure has three degrees of freedom in space and it consists of three active joints (two of them are prismatic and one is rotational). The passive joints are two cylindrical joints, one prismatic joint and one Cardan joint. The robot must position the end of the laparoscope, namely the video camera in any point of the operational field.
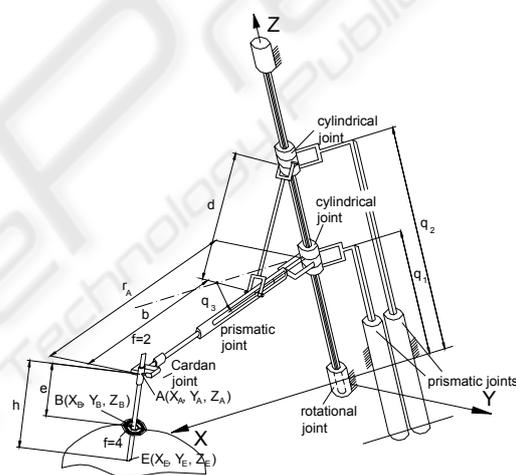

Figure 1: Kinematic scheme of the new parallel robot.

The particularity of this motion is the fact that the endoscope will move around a fixed point in space, which is the entrance point of the trocar in the abdominal wall of the patient (namely the point B). The presence of the passive Cardan joint before the laparoscope will allow the motion around the fixed point of the abdominal wall. The trocar, the abdominal entrance point and the endoscope can be seen as a virtual joint with four degrees of freedom, which allow the camera the rotation around the three axis and a translation parallel with the axis of the trocar. Thus, the endoscope can be positioned in any point of the abdominal area using the three degrees of freedom of the robot. The geometrical parameters of the PARAMIS robot are given by b, d, h; X_B, Y_B, Z_B (figure 1). In (Plitea, 2007) the inverse and direct geometric and kinematic

models for speeds and accelerations of the structure have been already presented.
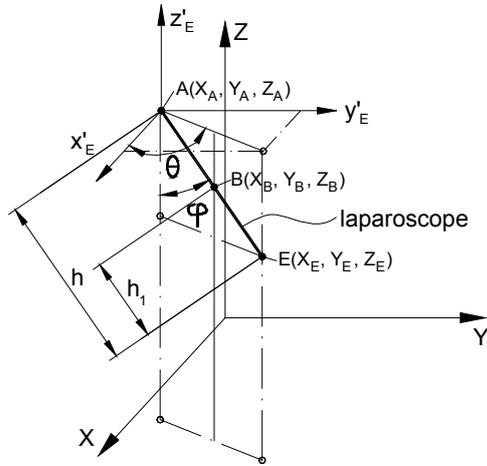

Figure 2: The angles of the passive Cardan joint: φ, θ.

The implicit functions equation system, which has been obtained from the kinematic model, are:

$$\begin{cases} f_1(X_E, q_1, q_2, q_3) \equiv X_A - \left[b + \sqrt{d^2 - (q_2 - q_1)^2} \right] \cdot \cos q_3 = 0 \\ f_2(Y_E, q_1, q_2, q_3) \equiv Y_A - \left[b + \sqrt{d^2 - (q_2 - q_1)^2} \right] \cdot \sin q_3 = 0 \\ f_3(Z_E, q_1) \equiv Z_A - q_1 = 0 \end{cases} \quad (1)$$

With the notations:

$$\dot{X} = [X_E, Y_E, Z_E]^T, \quad \dot{q} = [q_1, q_2, q_3]^T \quad (2)$$

Through derivation of the relations (1), it yields:

$$A \cdot \dot{X} + B \cdot \dot{q} = 0 \quad (3)$$

where A is the Jacobian matrix of the direct kinematics and B is the Jacobian matrix of the inverse kinematics, x the vector of end-effecter coordinates and q the vector of generalized coordinates of the actuators.

The form of the A and B matrices are:

$$A = \begin{bmatrix} \dfrac{\partial f_1}{\partial X_E} & \dfrac{\partial f_1}{\partial Y_E} & \dfrac{\partial f_1}{\partial Z_E} \\ \dfrac{\partial f_2}{\partial X_E} & \dfrac{\partial f_2}{\partial Y_E} & \dfrac{\partial f_2}{\partial Z_E} \\ \dfrac{\partial f_3}{\partial X_E} & \dfrac{\partial f_3}{\partial Y_E} & \dfrac{\partial f_3}{\partial Z_E} \end{bmatrix} \quad (4)$$

$$B = \begin{bmatrix} \dfrac{\partial f_1}{\partial q_1} & \dfrac{\partial f_1}{\partial q_2} & \dfrac{\partial f_1}{\partial q_3} \\ \dfrac{\partial f_2}{\partial q_1} & \dfrac{\partial f_2}{\partial q_2} & \dfrac{\partial f_2}{\partial q_3} \\ \dfrac{\partial f_3}{\partial q_1} & \dfrac{\partial f_3}{\partial q_2} & \dfrac{\partial f_3}{\partial q_3} \end{bmatrix} \quad (5)$$

3.1 Singularities Analysis

An important problem for the parallel robots is to identify and avoid singularities, ensuring the system stability and kinematic accuracy. Physically, these singular positions lead to an instantaneous change in the system number of degree of freedom and hence loss of controllability and degradation of the natural stiffness. Therefore it is important to identify singular configurations at the design stage in order to improve the system performance. For an optimal robot control these positions should be identified and avoided from the robot workspace.

A number of papers have studied the singularity problem for close kinematic chains (Merlet, 2005), (Sefrioui, 1992), (Park, 1999), (Romdahne, 2002).

The used algorithm for the PARAMIS structure singularity analysis is based on the deriving the determinants for the two Jacobian matrices derived from the inverse and the direct geometric model.

Singularities of Type I. First type of singularities occurs when the determinant of the Jacobian matrix B is zero.

Using (1), it yields:

$$\det(B) = \frac{q_2 - q_1}{\sqrt{d^2 - (q_2 - q_1)^2}} \cdot \left[b + \sqrt{d^2 - (q_2 - q_1)^2} \right] \quad (6)$$

If det(B)=0, physically, the parallel robot looses one or more degrees of freedom.

<u>Case 1</u>. $q_1 = q_2$ - The mechanisms is locked. The situation corresponds to the positioning on the horizontal plane of the rod of length d (the first extreme position).

<u>Solution</u>. Constructively, the mechanical structure of the robot will impose $q_1 < q_2$

<u>Case 2</u>. $d^2 = (q_2 - q_1)^2 \equiv d = q_2 - q_1$ - The mechanisms is locked. This situation corresponds to the positioning on the vertical axis of the rod of length d (the second extreme position).

<u>Solution</u>. Constructively, the structure of the robot will not allow displacements so long as the rod of length d to reach a vertical position.

Case 3.

$$b + \sqrt{d^2 - (q_2 - q_1)^2} = 0 \quad b > 0 \quad \sqrt{d^2 - (q_2 - q_1)^2} > 0$$

is impossible (as they represent lengths of mechanical components).

Singularities of Type II. Second type of singularities appears when the determinant of the Jacobian matrix A is zero.

Using (1), it yields:

$$\det(A) = \left(1 - \frac{h}{h_1}\right)^2$$

If det(A)=0, the system gains one or more degrees of freedom.

Case 1. $h = h_1$ it yields a point where the robot cannot be controlled. In case of the point A will superpose over point B.

Solution. The attachment mechanism of surgical instruments on the robot and the shape of the trocar will not allow point A to superpose over point B. (In this situation the instrument or laparoscope will be situated entirely in the patient).

Case 2. $h_1 = 0$, correponds to the situation when the laparoscope is positioned completely out of the surgical field, with $E \equiv B$ situation which will be impossible to attain with the robot, as the insertion and removel of the laparoscope is done manually by the surgeon.

The **Third Type of Singularities** so called "architectural singularities" takes place when both Jacobian determinants are zero.

Superposing the cases when the two determinants are equal with zero, it can be easily seen that in none of the above situations the determinants cannot be null in the same time. In conclusion, from the constructive point of view, for the functioning conditions imposed, there are no singularity points of type III.

These types of singularities can be easily avoided in the design stage.

Based on the fact that the only singularity cases appear in areas where the positions that the robot cannot attain it can be concluded that, in the working space of the robot, there are no points where the robot cannot be controlled.

4 WORKSPACE MODELING

For the geometrical determination of the working space of point E (the laparoscope extremity where the camera is placed) the first step is the determination of the working space of point A and its projection, keeping in mind that for on the segment ABE the point B is fixed in space and AE has a constant length.

The working space of point A can be easily determined, by determining the cross-sections within the working space in a parallel plane with OXY which for the limits imposed for q_1 and q_2 will have the same shape for any position of the Z axis.
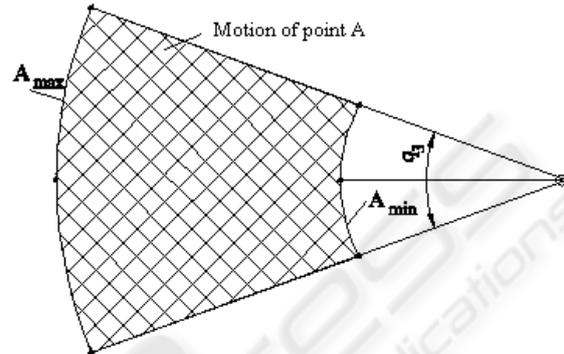
Figure 3: Motion of point A in a parallel plane with OXY (horizontal).

The hatched area in Figure 3, represents all the possible coordinates that point A can attain in a horizontal plane. Generating the three-dimensional working space it results the shape presented in Figure 4.
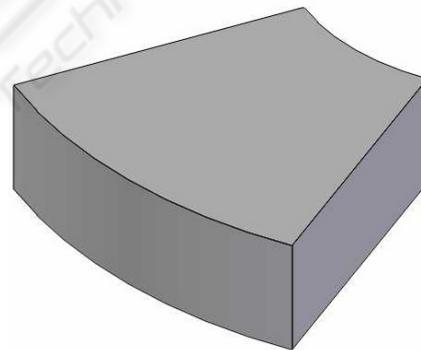
Figure 4: The workspace of point A.

For the workspace generation for point E has to be considered that the laparoscope (or any other surgical instrument) has a constant length and will always pass through a fixed point in space. The working space of point E by generating two intermediate working spaces whose intersection will represent the effective working space. The first intermediate working space is generated by projecting the point A from sections parallel with OXY plane. The second one is generated from sections of the working space of point A perpendicular on the plane OXY.

The intersection of the two intermediary volumes will result in the working space of point E presented in Figure 5.

Figure 5: The workspace of point E.

5 SIMULATION PROGRAM FOR PARAMIS PARALLEL ROBOT

A complex simulation program was developed in order to study the geometric, kinematic and dynamic characteristics of parallel robots with different degrees of freedom (Pisla, 2001), (Pisla, 2005).

This simulation system consists of the following modules:

-the geometrical module (GM) defines the robot geometric structure;

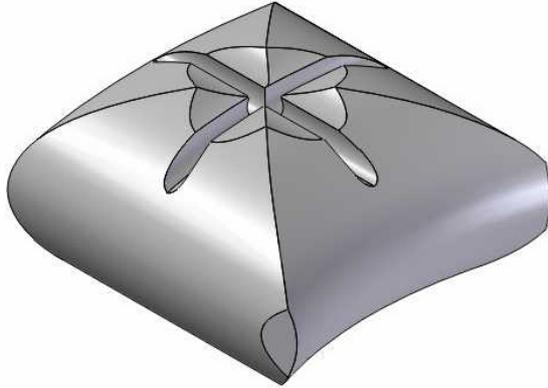-the kinematic module (KM) defines the parallel kinematic structure. The KM consists of: the algorithms for the kinematics, the algorithms for workspace generation and for singularities identification;

-the modeler (MM) represents the combination of the geometrical representations, kinematic descriptions and the adequate disposition of different objects;

-the simulator (SM) has the main task to compute the current state of the parallel robot with respect to certain instructions such as: the robot source program or signals which are generated by sensors;

-the graphical module (GPM) is responsible with the simulated robot transformations and screen graphical visualization.

The simulator is interactively achieved such as the user could influence the simulation parameters and could be informed about the possible errors during the simulation process.

The simulator determinates the next robot state, independent of the input mode. If an error appears, the user is informed through an error message with its type and elimination way. The simulator is interactively achieved such as the user could influence the simulation parameters and could be informed about the possible errors during the simulation process.

The data exchange between simulation system modules is achieved through data files, which allow future module integration in the existing system and makes easy the data exchange with another off-line programming systems.

For the graphical modeling of the parallel structures it was used Solid Edge$^{©}$, one of the most advanced software for computer aided design, available on the market (www.solidedge.com). This program was selected especially for its outstanding performances in terms of stability and user-friendly interface, and even more for its total compatibility with Visual Basic.Within the simulation system the virtual graphical model of parallel structures has been created.

The geometric parameters of the parallel structure can be modified within the 3D modeling software (Solid Edge Assembly) influencing the simulation environment. The assembly relations between parts, between subassemblies or between parts and subassemblies can be also modified (Pisla, 2001), (Pisla, 2004).

The program has the possibility to select the parallel structure from a list in accordance with the class of the mechanism and its degree of freedom.

The parallel structure parameterization enables the possibility to develop a study regarding the geometric optimization and the robot workspace shape.

The results obtained are useful for the designers not only to understand the distribution of characteristics of the workspaces for various geometrical parameters of parallel structures, but also to optimize the parallel robots.

The presented simulation system enables the motion visualization, it is valid for any structure of parallel robot enabling to introduce the kinematic model over the virtual robot the single foreseen limit being the hardware computing capacity. The introduction of extra conditions related to any element, joint or overall behaviour of the robot is possible with a small number of actions.

These facilities of the simulation software enable the possibility to develop a complex study about the kinematics and dynamics in order to optimize the parallel structure.

Figure 6: Simulation of the PARAMIS parallel structure.

In Figure 6 is presented the graphical interface for graphical modeling for different parallel structures. The kinematic algorithms have been implemented in the kinematical module (Kinematics). In the simulation is included the parallel robot with the instrument and the virtual human body.

Within the simulation system (Figure 6) the virtual graphical model was created. The 3D functional model of the parallel structure allows the designer to understand better its form and its functionality. Using the Solid Edge Assembly module it is possible to impose the assembling conditions between the components including the mounting possibilities and the tolerance for and between the parts.

Figure 7: The PARAMIS robotic system.

The simulations were performed using the parallel robot presented in figure 7 which manipulates the laparoscope in the virtual human model to ensure also the fixed point in the working space of the robot (point B from Figure 1).

The virtual model was used for the validation of the geometrical model. For that, the robot was placed in an arbitrary position and all its parameters measured, including the point B (Figure 1). The second step was the computation of the coordinates of the point E in parallel with their measurement on the virtual model (Figure 8).

The calculated results based on the equations matched 100% with the ones given by the virtual model.

Figure 8: Validation of the geometric model.

The second goal concerning the virtual model was its use for the simulation of the robotic structure in the medical environment created. In this stage it was important to achieve proper motions for different commands in the active joints. Solid Edge allows a the definition of motion trajectories in terms of displacements, speeds and accelerations as points, lines or equations implemented in the active joints, as shown in figure 9.

Figure 9: Input of motion trajectory in a module.

The simulation enabled the validation of the structure from the points of view of both engineers and surgeons and opened the way for the next step in the PARAMIS robotic design evolution, the construction of an experimental model.

6 CONCLUSIONS

Modeling and simulation are important and essential stages in the engineering design and problem solving process because it allows to prevent the risks and to lower the costs that appear with the design, construction and testing stage of a new robot. Since parallel mechanisms have a complex structure, using the proposed approached of modeling and simulation will lead to an increased efficiency in developing new structures.

In the paper the modelling and simulation of the PARAMIS new parallel robot is presented. The simulations results obtained with the developed simulation system for parallel robots allow a structure verification before a parallel robot is built.

The developed simulation system for the parallel robots offer multiple advantages: modularity of the simulation system for parallel robots; friendly graphical user interface of the simulation system; possibility for parallel structure parameterization; possibility to generalize some parallel structures; Identification of singularities; possibility to identify the optimal working zone; workspace generation: the structures verification before a parallel robot is built.

In this case, the contribution is the use a virtual reality definition system to create the virtual objects (bodies) that includes shape, dimensions, mass and center of mass, surface characteristics and the deviations from these characteristics may be also considered. Between the virtual objects are defined the appropriate structure joints. The type of joint, their constructive dimensions, together with the actuating define the motion restrictions that are encapsulated within the subassemblies.

Over the predefined virtual structure is applied the kinematic model using a programming interface in Visual Basic ensuring the PTP or the path control motion.

The presented simulation system enables the motion visualization, enabling to introduce the kinematic model over the virtual robot the single foreseen limit being the hardware computing capacity. The introduction of extra conditions related to any element, joint or overall behavior of the robot is possible with a small number of actions. The up-to-date results validated the solution creating the premises for the next step, the construction of the experimental model for the PARAMIS robot.

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