KINEMATIC ANALYSIS OF A HYBRID DELTA- REMOTE CENTER OF MOTION (RCM) ROBOT ASSISTING MINIMALLY INVASIVE SURGERY

PHÂN TÍCH ĐỘNG HỌC ROBOT DELTA - RCM HỖ TRỢ PHẪU THUẬT NỘI SOI

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Abstract - Minimally Invasive Surgery (MIS) is the latest trend of surgery in which the surgical operation is done through small incisions. This type of surgery has more advantages than conventional surgery such as shorter and less painful recovery, less invasive, safer... However, there are some disadvantages associated with MIS such as limited field of view by using endoscopes and limiting motion of surgical tools. In order to overcome these disadvantages of MIS, almost of all existing robotics that assist Minimal invasive surgery, have the Remote Center Motion mechanisms. This paper presents an overview of some typical Remote Center of Motion (RCM) mechanisms with graphical result conducted simulation on ADAMS VIEW and kinematic analysis of a compact hybrid Delta – RCM robot that is developed for assisting physicians to perform MIS.

Key words - Delta robot; Parallel robot; Remote Center of Motion; Kinematic analysis; Minimally Invasive Surgery

Tóm tắt - Phẫu thuật nội soi là một phương pháp phẩu thuật thông qua những lỗ nhỏ trên người bệnh nhân. Phương pháp này có nhiều ưu điểm hơn so với phương pháp mổ truyền thống như thời gian phục hồi nhanh hơn, vết sẹo mổ nhỏ hơn, ít đau hơn và an toàn hơn. Tuy nhiên, trong phẩu thuật nội soi, mọi hoạt động phẩu thuật đều thông qua các lỗ nhỏ nên bị giới hạn về không gian quan sát, và dụng cụ phẩu thuật cũng bị giới hạn về vùng chuyển động. Để khắc phục các nhược điểm này, nhiều robot trang bị cơ cấu chuyển động quanh một tâm (Remote Center of Motion mechanism) đã được nghiên cứu. Bài báo này sẽ trình bày mô phỏng chuyển động của một số cơ cấu RCM thường gặp trong các robot hỗ trợ phẫu thuật nội soi và trình bày phân tích động học của robot Delta – RCM được đề xuất bởi nhóm tác giả.

Từ khóa - Robot delta; robot song song; Remote Center of Motion; phân tích động học; phẫu thuật nội soi.

1. Introduction

Nowadays, Minimal Invasive Surgery becomes more and more common in hospitals. It is a surgical method that is done through one or more small incisions, using specialized techniques and instruments like small tubes, tiny cameras, and surgical instruments to access the operative region. Because this operating procedure is performed through a small incision instead of large opening like the conventional surgery, patients feel less painful, have less scarring and quicker recovery times. However, surgeons still meet many difficulties to perform complex procedures due to technical limitations inherent in laparoscopic surgery such as shaking problem of the tiny camera during operation or limited vision of the field. That is one of the reasons why Robotic assisting surgery was developed to overcome these problems and enhance the precise movements of the surgeon's hands because endoscopes fixed to the robotic arm are more stable than hand-held endoscopes.

Since the introduction of robot-assisted surgery in the early 1980s, there are many kinds of Robotics assisted minimally invasive surgery has been introduced and the most famous one is The *da Vinci* surgical robot that is developed and marketed by Intuitive Surgical Inc. (Sunnyvale, CA). This robot has brought minimally invasive surgery to more than 3 million patients worldwide. In 2013, Department of Mechanical and Aerospace Engineering Monash University, Melbourne, Australia designed and implemented a novel parallel robot that assisted minimally invasive surgery system with name PRAMISS [2] that is able to approach micro manipulations under the constraint of moving through a remote center of motion point. This robot is composed of a 6-DOF Gough-Stewart manipulator and RPRR mechanism fixed to the moving platform of the parallel manipulator (Figure 1).

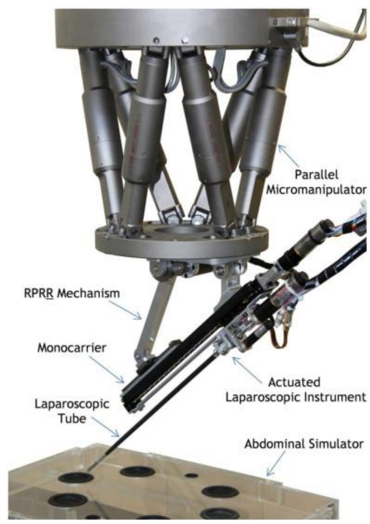

Figure 1. *PRAMISS robot [2]*

Professors at The Chinese University of Hong Kong developed 4 DOF robot assistant for uterus positioning during hysterectomy [3]. The robot assistant is composed of a 3-DOF robotic positioning arm, a 1-DOF motorized uterus manipulator, and a supporting stand of the robot as shown in figure [3]. Or researchers from Tianjin University, China proposed a Novel Spatial Remote Center-of-Motion robot for assisting surgeons to perform Minimally Invasive Surgical [4]. This robot has 4 DOF with the wrist as a 2-DOF parallel mechanism (Figure 3). In this paper, the kinematic of a novel hybrid robot consisting of a DELTA parallel manipulator and an additional remote center of motion mechanisms attached to the moving platform is presented.

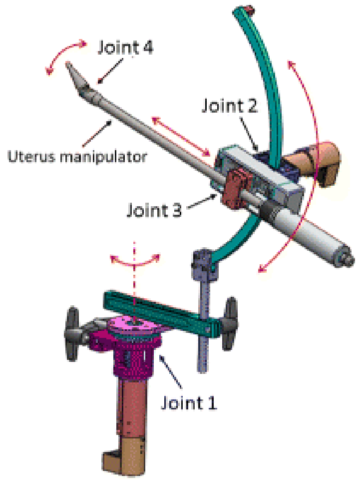

Figure 2. *Four DOF robot assistant for uterus positioning during hysterectomy [3]*

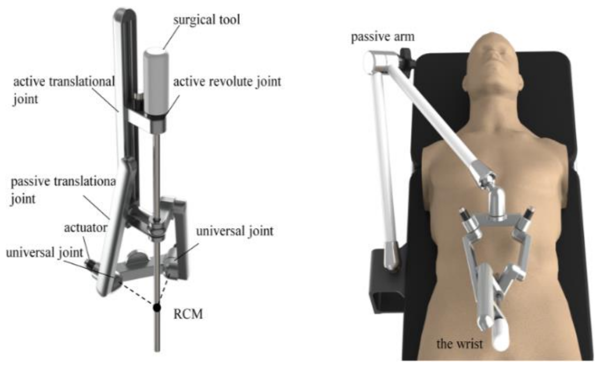

Figure 3. *4 DOF Spatial Remote Center-of-Motion robot [4]*

2. Typical remote center of motion mechanisms

In MIS surgery, the MIS robot must insert its instruments inside the patient's body through a small incision and manipulate them around this fixed point on the patient's body. In order to improve the security of minimally invasive surgical robot, many remote center of motion mechanisms have been devised and they can accomplish these required motions. The following part will explains some typical remote center of motion mechanisms.

Parallelogram mechanism

This mechanism is designed based on a parallelogram structure, which can easily compose 2-DOF RCM mechanisms (the tilt and pan rotational DOF). Figure 4 shows the basic concepts of generating an RCM via the parallelograms. Compared with the serial structure, this mechanism has higher stiffness and large movement range.

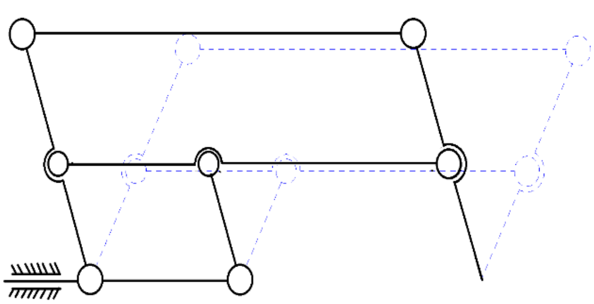

Figure 4. *Parallelogram mechanism*

Many robotically assisted surgical systems use the parallelogram based design as their RCM mechanisms. For example, RoboMaster 1 developed by Sharif University of Technology, Iran [5], the dual-triangular mechanism (DT-linkage) [6] or The da Vinci robotic surgical system. Figure 5 shows the result of simulation of 2 DOF RCM mechanism based parallelogram structure on Adam Views.

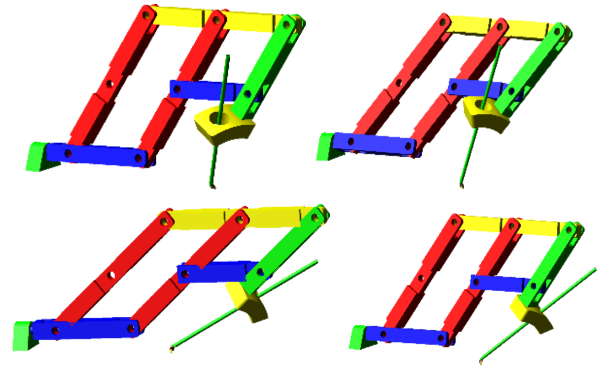

Figure 5. *Simulation of Parallelogram mechanism*

Circular tracking arcs

This is also another kind of RCM mechanism with two rotational degrees of freedom shown in Figure 6, one is generated by sliding a joint that place on the circular track as the base and the other rotational DOF is produced by rotating the circular track whereas the rotational joint's axis must go through the center of the circle of circular track. A novel RCM parallel manipulator for minimally Invasive Celiac Surgery proposed by Shanghai University of Engineering Science, Shanghai 201620, China [7] uses this structure. The result of simulation of 2 DOF RCM mechanism basing this structure on Adam Views is shown in Figure 7.

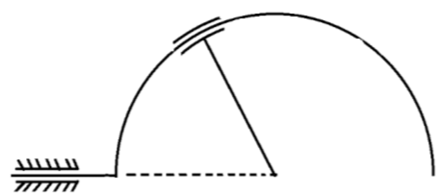

Figure 6. *Circular tracking arcs*

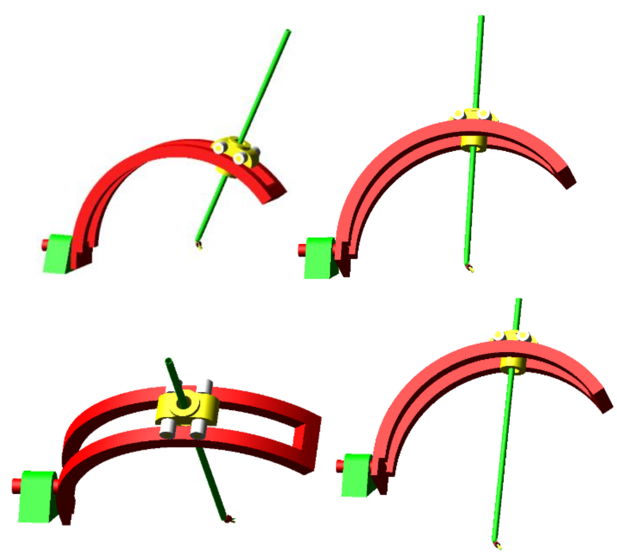

Figure 7. *Simulation of 2-DOF Circular tracking arcs*

Spherical mechanism

Another RCM mechanism is based on spherical linkages which rotate about the center of the sphere and all axis of revolute joints intersect at the center of the sphere (Figure 8). Some researchers focus on developing this kind of mechanism to improve the quality and reduce singularity. Many robots have been devised via the spherical linkages, such as A PROMIS (Prime RObot for Minimally Invasive Surgery) system or curved RCM of surgical robot arm - MEERE company [8].

In this study, we use a spherical serial two link mechanism to demonstrate the motion of our proposed robot.

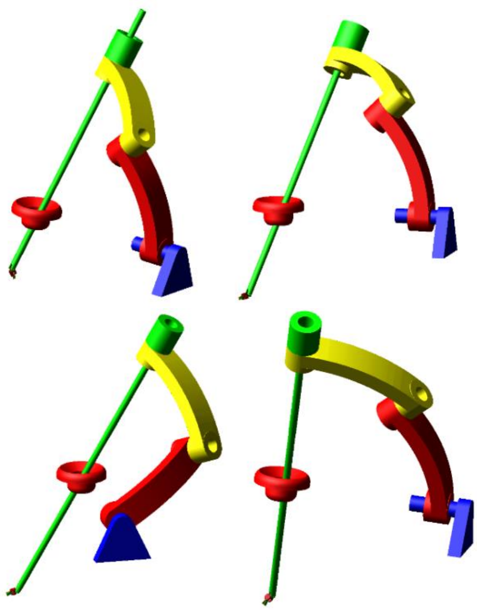

Figure 8. *Simulation of 2-DOF spherical mechanism*

3. Kinematic analysis of hybrid Delta – RCM robot

The hybrid Delta - RCM robot is inspired by compositing the Delta parallel manipulator with a spherical serial two link mechanism. The general computer-aided-design (CAD) model of the hybrid Delta - RCM robot is depicted in Figure 9. This manipulator could be split within two main structures, one is Delta robot and the other is RCM mechanism. The Delta robot is a famous 3-DOF translational parallel mechanism that consists of a moving platform connected to the fixed base through three legs. Each leg contains a prismatic joint activated by actuators in the fixed platform. The motion is transmitted to the mobile platform through parallelograms formed by links and spherical joints. RCM robot of this study is a member of a class of spherical mechanism that is explained in section 2.

In order to implement the kinematic of this manipulator, the coordinate axes are fixed to the various joints of the robot. The frame OXYZ is fixed to the base with O at the center of the triangle $F_1F_2F_3$ with Z axis perpendicular to the platform. The frame coordinate of $O_1X_1Y_1Z_1$ is attached to the moving platform $N_1N_2N_3$ with its Z_1 axis pointing upward and being normal to the platforms as shown in Figure 9. The frames of the spherical mechanism are assigned so that the Y axes can point outward along the revolute joints.

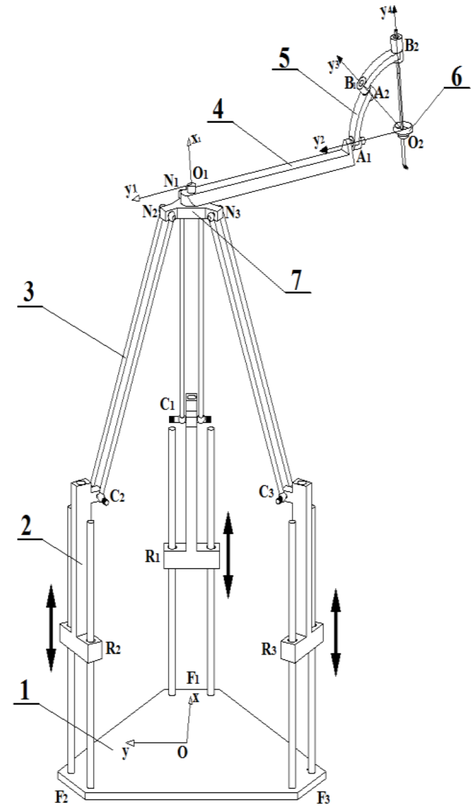

Figure 9. *Hybrid Delta – RCM robot*

1. The fixed platform; 2. The prismatic joint runner; 3. Parallelogram link; 4. Extension arm; 5. Spherical link; 6. The trocar (Pivoting point); 7. Moving platform.

The coordinates of F_i (i=1,2,3) are in frame Oxyz:

$$F_i\{Oxyz\} = R_i * \begin{bmatrix} R \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

The coordinates of N_i (i=1,2,3) are in frame $O_1X_1Y_1Z_1$

$$N_i\{O_1\} = R_i * \begin{bmatrix} r \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

Where $R_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 \\ \sin\theta_i & \cos\theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix}$ is the rotation matrix $\theta_i = (i-1) * \frac{2\pi}{3}$

Hence, the coordinate of Ni is relative to the original of the fixed platform

$$N_i\{O\} = T_N * [N_i\{O1\}, 1]^T \quad (3)$$

Where $T_N = \begin{bmatrix} 1 & 0 & 0 & x_{O1} \\ 0 & 1 & 0 & y_{O1} \\ 0 & 0 & 1 & z_{O1} \\ 0 & 0 & 0 & 1 \end{bmatrix}$ is the translation matrix

We assume that all the lengths of six parallelogram linkages of the DELTA robot are identical L_i = NiCi (i = 1,2,3), as well as the length of the individual joints defining the configuration of each leg is denoted by Z_{Ci} (i = 1,2,3). Let O1 be a point located on the moving platform, then the coordinate of point O1 can derive from three constraint equations of robot

$$L = \|\overrightarrow{N1C1}\| = \|\overrightarrow{N2C2}\| = \|\overrightarrow{N3C3}\| \quad (4)$$

Substitute (1), (2) and (3) into (4):

$$\begin{cases} L^2 = [R-(r+x_{O1})]^2 + y_{O1}^2 + [z_{C1}-z_{O1}]^2 & (5) \\ L^2 = [-\frac{R}{2}-(-\frac{r}{2}+x_{O1})]^2 + [\frac{\sqrt{3}}{2}*R-(\frac{\sqrt{3}}{2}*r+y_{O1})]^2 + [z_{C2}-z_{O1}]^2 & (6) \\ L^2 = [-\frac{R}{2}-(-\frac{r}{2}+x_{O1})]^2 + [\frac{\sqrt{3}}{2}*R-(-\frac{\sqrt{3}}{2}*r+y_{O1})]^2 + [z_{C3}-z_{O1}]^2 & (7) \end{cases}$$

Let a1, a2 be the arc length of spherical links A_1A_2 and B_1B_2 respectively and r_1, r_2 be the radius of links.

Assume θ_1 and θ_2 are the actuated angle of revolute joints of the spherical mechanism. And the coordinates of A_2 and B_2 are in frame $O_2X_2Y_2Z_2$

$$A_2\{O_2\} = R_y(\theta_1).R_z(a_1).A_1\{O_2\} \quad (8)$$

$$B_2\{O_2\} = R_y(\theta_1).R_z(a_1).R_y(\theta_2).R_z(a_2).A'_1\{O_2\} \quad (9)$$

Where $R_y(\theta)$ and $R_z(\theta)$ are the rotation matrix by angle θ about the y and z axis in three-dimensions.

4. Simulation

In order to check the functionality of model construction and evaluate the performance of the manipulator, the simulation is conducted before the real platform is available. In this study, the mechanical construction is performed with CAD software Unigraphics and the input data is exported to ADAMS as a simulation tool for the mechanical system. The result of simulation is shown in Figure 10 to Figure 16

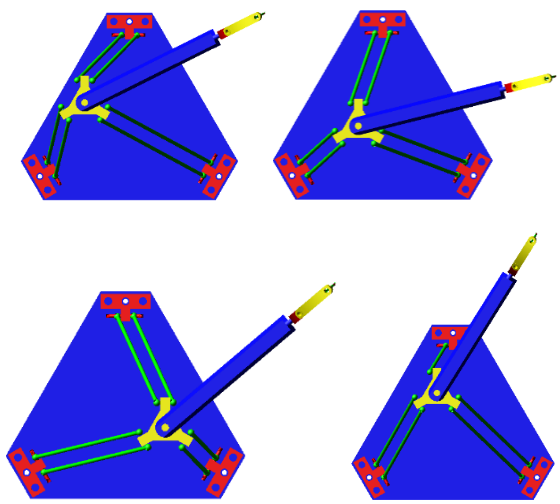

Figure 10. *Simulation result of Hybrid Delta – RCM robot*

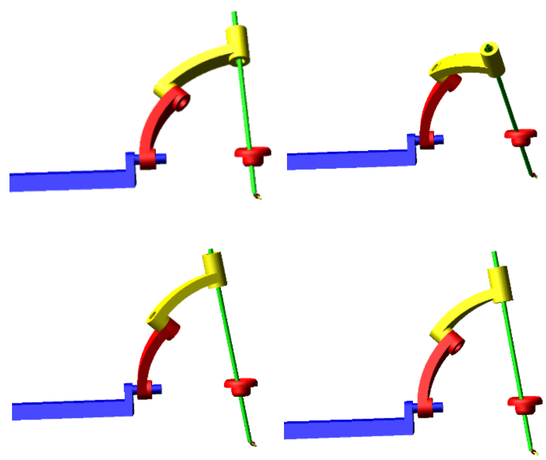

Figure 12. *Simulation result of RCM mechanism*

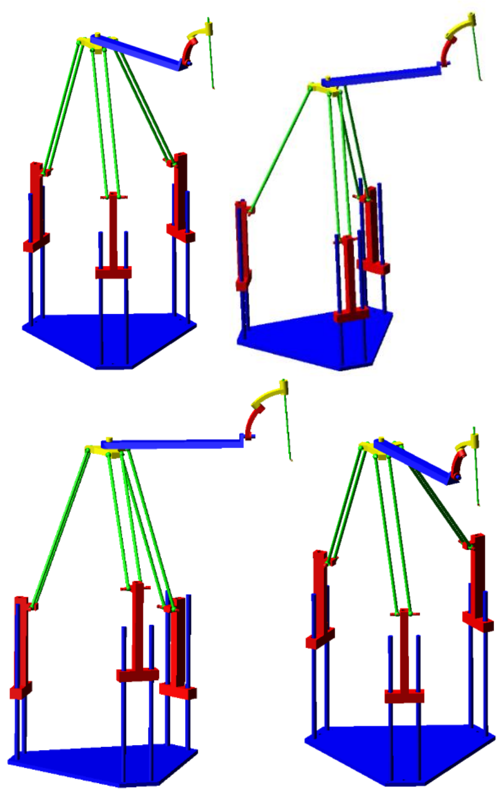

Figure 11. *Simulation result of Hybrid Delta – RCM robot*

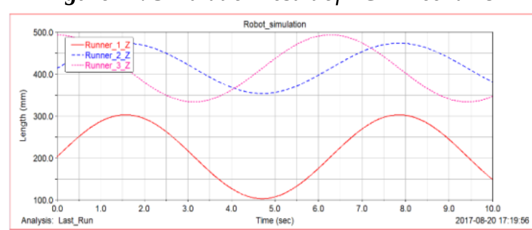

Figure 13. *Position of the prismatic joints*

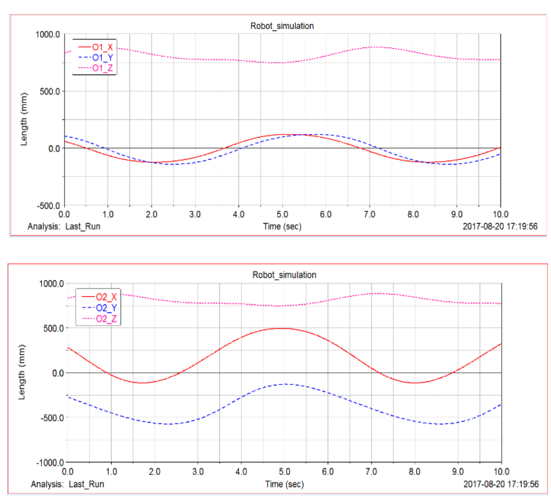

Figure 14. *Position of point O1 and O2*

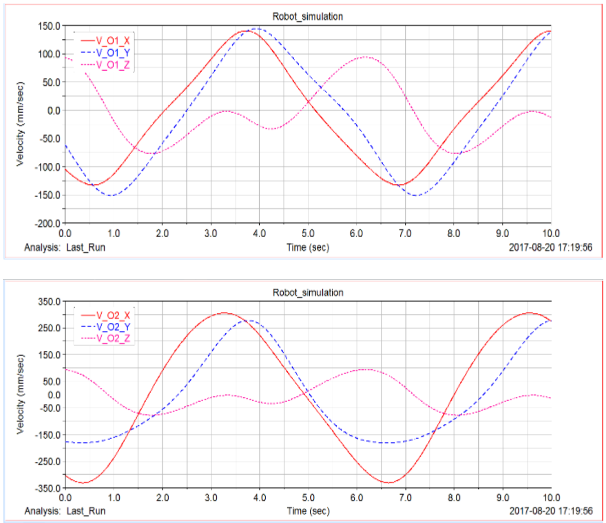

Figure 15. *Velocity of point O_1 and O_2*

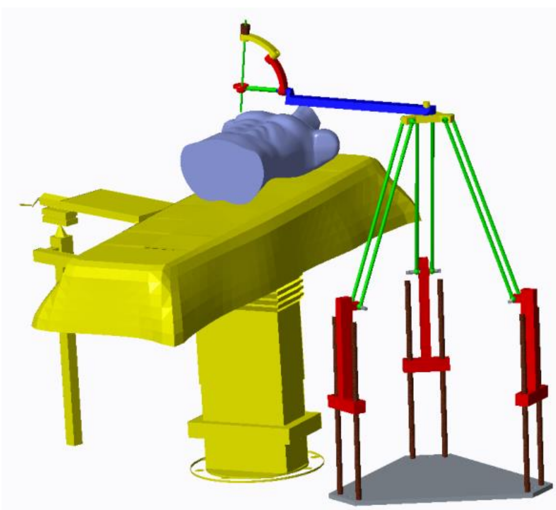

Figure 16. *3D model of robot*

5. Conclusion

This research presents an overview of some typical RCM mechanisms and proposes a new concept of hybrid Delta – Remote Center of Motions robot that merges the 3-DOF Delta parallel robot with prismatic actuators and a RCM mechanism for assisting minimally invasive surgery. The 3D model construction and performance of proposed manipulator is evaluated using ADAMS VIEW software. In the future, we will build a real robot with integrated controller system for testing.

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