

Applications of a 3-Revolute Orientation Sensing Mechanism (3-ROSM) in Controlling a Camera

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Abstract: *In controlling the orientation of an object, it is always desired to have a more intuitive form of controller or an input device as it helps the user adapt to it at a faster pace, hence making it more productive. This paper focuses on the development of a prototype and application of an intuitive serial chain mechanism to measure orientation. This user driven mechanism, referred to as 3-Revolute Orientation Sensing Mechanism (3-ROSM), proposed elsewhere by the authors, is a serial chain mechanism with three intersecting axes and has rotary encoders to measure the joint angles. It is also gravity balanced to prevent reorientation of its links due to the action of gravity. This reduces the effort needed by the user to move its links and also its dependence on load bearing servo motors. It also emulates the joint system in a human wrist and reduces the overall load acting on the user's hand while gripping the end-effector. The gravity compensation is achieved through the placement of counterweights along and orthogonal to the joint axis under consideration. This makes the 3-ROSM more adaptable to desirable or undesirable load variations. The additional features of this device are its simplicity, low cost, energy efficiency and wide available workspace with which the user can operate this device. To demonstrate its usability and versatility, an easy to assemble physical prototype of the 3-ROSM was designed and developed, which has encoders mounted on its joint axes and was used in two different applications. First, in controlling a 3-axis motorized camera mount and second, navigating the position and orientation of the view-camera in a CAD software.*

Keywords: *gravity compensation, serial mechanism, orientation controller*

1. INTRODUCTION

In most 6-axis industrial robot arms, the first three axes can be actuated to bring the arm to the desired position and the last three axes control the orientation of the wrist. Therefore, it is easier to decouple the control of position and orientation separately to reduce the complexity in using the controller. One type of frequently used position and orientation controller is the teach pendant which incorporates the use of buttons to increase or decrease the value of change in joint angles. Although this method is simplistic, it lacks intuitiveness which makes the coordinated motion of the end-effector difficult and also, there exists a high probability of operator disorientation [1]. Therefore, an intuitive device to control the orientation is desirable.

Another type of orientation control is obtained with the use of parallel mechanisms, in which the user can achieve high accuracy in orienting the end-effector. Long et.al (1992) proposed the use of a six-DOF generalized master hand controller using three pantograph linkages which provided high mobility and stiffness in a compact design [2]. This was also demonstrated by Yoon et.al (2001) in the design of a haptic mechanism which utilized three servomotor driven pantograph mechanisms to drive an end-effector widening the effective workspace of the device [3]. An original design proposed by Birglen et.al (2002) incorporated the use of spherical links and revolute joints with the joint axes intersecting at a central point in the end-effector [4]. This device achieves pure rotation around a point located in the user's hand but has a restricted workspace. However, parallel mechanisms in general have complex kinematics and insurmountable kinematic singularities [5]. In contrast, serial mechanisms have simple constructions and the forward kinematic problem is easier to solve.

A successful input device should not only achieve accurate position and orientation control but should also neutralize moment acting on the links which may be caused by moving links or by gravity. This can be achieved through static balancing, also known as gravity compensation which is achieved when the total force acting on the fixed link due to the entire mechanism does not produce any torque under static conditions [6]. This can be achieved passively through the use of counterweights or springs [7] - [11], or actively through the use of pneumatic or hydraulic actuators. Gravity

compensation also reduces the effort required to move the links making it easier to control while conserving energy by reducing dependency on the external actuators.

A modified Gimbal mechanism, shown in Figure 1(a), having three intersecting joints can be used to measure the orientation of the end-effector. This can be achieved if the individual joint angles can be measured when the user rotates the end-effector sphere about its center. However, once the user ceases to hold the end-effector, the mechanism would move to its most stable configuration under the action of gravity. Hence, a gravity balancing method to avoid this is desirable.

The first and the last author proposed the 3-ROSM (3 Revolute Orientation Sensing Mechanism), in which passive gravity balancing was achieved for the mechanism shown in Figure 1(a) by modifying two links and placing counterweights at appropriate places [12]. As shown in Figure 1(b), the links of the mechanism denoted as Link1, Link2 and Link3 move about a fixed link (Link0 or Ground) and the axes of its respective joints (denoted as Joint1, Joint2 and Joint3). The three joints intersect at a point located at the center of the spherical gripper attached to Link3, also called the end-effector (EE). When the configuration of the device is changed, the centre of the sphere on the EE remains at the same position while its orientation changes according to the change in joint angles. The main idea was to make the net moment about a joint axis as zero such that for any joint angle, a particular joint would not have any motion due to gravity. As Link3 is axis symmetric, there was no need to modify its shape. Link1 and Link2 were modified to have a T-shaped extension on which counterweights can be mounted. If the masses are known, the distances at which they have to be placed can be determined from simple moment balance equations about the joint axis as reported in [12].

The CAD model of the proposed mechanism with counterweights was subjected to gravity test in Autodesk Inventor Dynamic Simulation module and it was verified that the mechanism was gravity compensated.

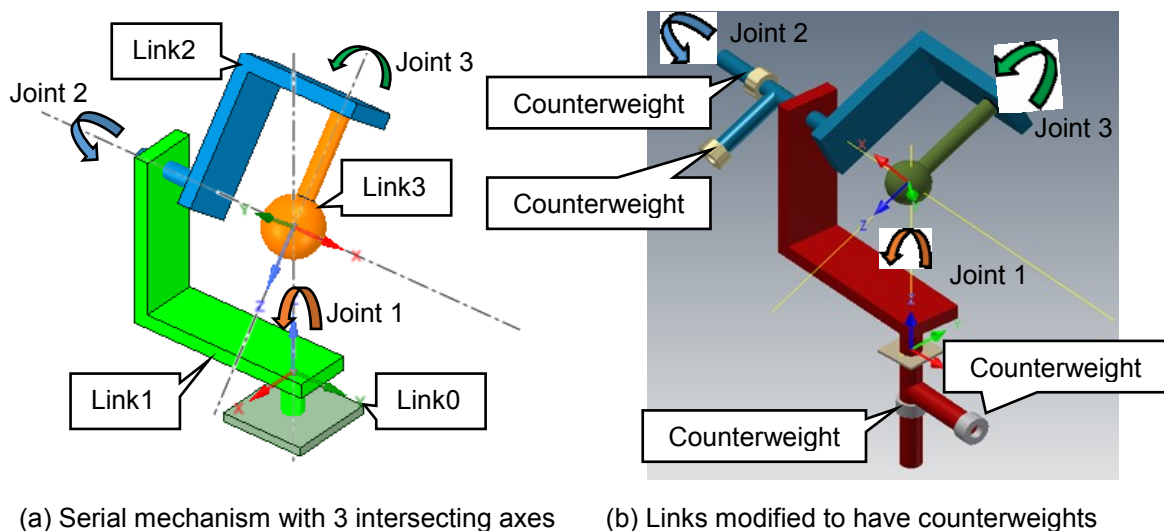


Figure 1 - CAD model of 3-ROSM (Antao et.al 2016)

After the verification of its principles using dynamic simulation, the first prototype of the mechanism was developed to propose and validate a method to determine the positions of the counterweights in a physical prototype and has been submitted elsewhere [13]. The second prototype, which is considered in this paper, is a 3D printed version which has rotary encoders to measure the joint angles, and incorporates passive balancing. Section 2 of the paper gives a brief overview on the kinematics of the mechanism followed by the procedure for obtaining the passive balance in Section 4. Subsequently in Section 5, the applications of the mechanism in controlling a 3-axis camera mount and controlling the position and orientation of the camera in a CAD software are elaborated, followed by the conclusions.

2. KINEMATIC ANALYSIS

The current prototype of the 3-ROSM has hollow bore rotary potentiometers as encoders to measure the joint angles, but in order to provide smooth control of the manipulator (ex. a camera mount) the joints of the prototype have to be mapped. As mentioned above, the axes of the joints of the 3-ROSM intersect at the center point in the end-effector, which being invariant enables the calculation of

change in joint angles with the help of forward kinematics. To aid with the study of the behavior of each joint with respect to the other, the design architecture of the 3-ROSM is represented using the Denavit Hartenberg (DH) representation which is a commonly used convention for selecting the frames of reference in robotics. The nomenclature and methodology described in [14] is followed in this paper. A single DH coordinate frame consists of four different DH parameters which are joint angle (θ), link offset (b), link twist (α) and link length (a) which give the geometric relationship between any two consecutive DH frames. Hence, they can collectively represent the position and orientation of any link in the system with respect to the DH coordinate frame attached on the previous link. Referring to Figure 2(a), the determination of the DH frames located on the 3-ROSM begins with assuming the orientation of Link 0 along the axis of Joint1 as the position of the EE remains invariant. As a result, the Z axis of frame₁ is taken along Joint axis 1 while the X axis is arbitrary. The Y axis is the cross product of the Z and X axes. As per DH representation convention the Z axis of the consequent frame (Frame₂) must be assumed along the direction of the joint axis of Joint1 which is again along Z₁ (Z-axis of Frame₁) direction resulting in a 0 twist angle, and X₂ is chosen to be orthogonal to Z₂. The difference in angle between X₂ and X₁ is considered as the Joint angle θ_1 which is a variable in this case. Hence, through the choice of the coordinate axes, the number of parameters needed reduces making the further assignment of DH frames simpler. Frame₃ with respect to Frame₂ is obtained on the central point of the EE along the axis of Joint2, with a joint offset of b_2 which is the distance between the central point and the fixed point on Link0. To orient Z₃ along the axis of Joint 2, a twist angle of 90° in the opposite direction must be applied and X₃ is taken as the common normal between Z₂ and Z₃. To further simplify the assignment of frames, the direction of X₃ is taken as (Z₃ × Z₂) and not (Z₂ × Z₃). This is also due to constraints placed on the prototype of the 3-ROSM in setting its initial configuration. Similarly, the axis of Joint3 intersects with Joint2 and the DH frame₄ is attached, as shown in Figure 2(b). The values of the DH parameters between all four DH frames are listed in Table 1.

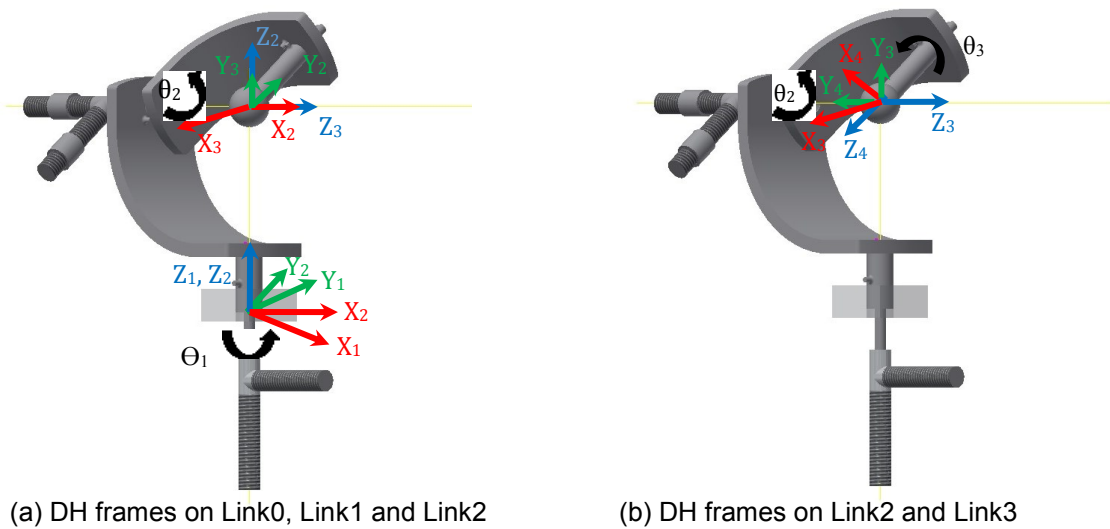


Figure 2 - DH frames attached to a prototype of the 3-ROSM

Table 1 - DH parameters of the 3-R Orientation Sensing Mechanism

Parameter Joint	Joint offset (b_i)	Joint Angle (θ_i)	Link Length (a_i)	Twist Angle (α_i)
Joint1	0	$\theta_1(\text{variable})$	0	0°
Joint2	b_2	$\theta_2(\text{variable})$	0	-90°
Joint3	0	$\theta_3(\text{variable})$	0	-90°

A Homogeneous Transformation Matrix (HTM) can be used to represent the configuration between two consecutive DH coordinate frames. Hence the HTM of the final Frame₄ with respect to the initial Frame₁ is given by the product of the HTMs on each individual joint denoted by T₁, T₂ and T₃ [12], as

$$\mathbf{T} = \mathbf{T}_1\mathbf{T}_2\mathbf{T}_3 = \begin{bmatrix} \cos(\theta_1 + \theta_2) \cos \theta_3 & \sin(\theta_1 + \theta_2) & \cos(\theta_1 + \theta_2) \sin \theta_3 & 0 \\ \sin(\theta_1 + \theta_2) \cos \theta_3 & -\cos(\theta_1 - \theta_2) & \sin(\theta_1 - \theta_2) \sin \theta_3 & 0 \\ \sin \theta_3 & 0 & -\cos \theta_3 & b_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

In the above HTM, the elements in the first three rows and columns represent the direction-cosines corresponding to the orientation between Frame₄ and Frame₁. The elements in the fourth column and first three rows represent the position vector from the origin of Frame₁ to Frame₄, represented in Frame₁, which remains invariant with respect to any change in joint angles, i.e., the position of the origin of Frame₄ with respect to Frame₁ does not vary for any configuration/orientation of the 3-ROSM. Equation (1) refers to the forward kinematic analysis which is the determination of EE configuration for given joint angles. Based on the joint angles, the control of the orientation of a camera can be controlled as explained in Section 4. The authors acknowledge the presence of a singularity when the axis of Joint3 aligns with Joint1 resulting in the loss of a degree-of-freedom. This issue will be addressed in further research on modification of the initial design of the 3-ROSM.

3. PASSIVE BALANCING OF THE 3-ROSM

Another feature of the 3-ROSM is that the mechanism is gravity compensated. This is to stop the mechanism from reorienting itself to a stable configuration when the user releases the EE, and also reduces the effort needed by the user to move the links. Passive balancing, through the use of counterweights is performed about the joints of the 3-ROSM. The theory applied in this mechanism is that the moment applied by the links due to gravity is countered by an equal and opposite moment applied by the counterweights. To accommodate the counterweights, the initial system of the mechanism was modified by placing T-shaped extensions which enable the counterweights to be placed along and orthogonal to the joint axis and thereby reduce the complexity of the balancing problem from 3D to two problems in 2D. Passive balancing using this methodology was first conducted on a CAD model as explained by Antao et.al (2016) and subsequently, an initial physical prototype was designed to test and validate this method and also posed challenges in finding the practical centre of mass which is necessary due to several inaccuracies arising in Centre of Gravity (CG) calculations, which may be due to manufacturing irregularities, material defects etc. The method applied in finding the CG of the various links of the 3-ROSM is referred to as the Hanging Method [15]. This method involves suspending a link by different points from a fixture and dropping a vertical plumb line from the same fixture. The intersection of two plumb lines for different orientations of the link is taken as its CG. Also, a third plumb line is also dropped for a different link orientation to validate the intersection point. The plumb line and threads (considered mass less) by which the link is hung, should be in line and parallax must be avoided to produce an accurate result. In some cases, the CG does not lie on the link itself but off the link, on the same plane. To map these types of points, the link is attached to a paper (considered mass less) which acts as the plane upon which the CG can be plotted with the help of the Hanging Method. The research involved in the development of this initial prototype with the correlation of CG values found by theoretical means and using the hanging method, is reported in [13].

Thereafter, the Hanging method was also used to find the CG locations in the current prototype developed by 3D printing technology. A few images taken while finding the CG location are shown in Figure 3. The encoders were placed on the links such that they are also symmetric about the same plane as the links of the prototype. After locating the CG locations, the values were put into moment balancing equations [12]. The mass of the counterweight were predefined and only the locations on the T-shaped extensions had to be found. It should be noted that due to light weight of the 3D printed model of the 3-ROSM, changes in the mass such as addition of wires to the encoders, affect the overall CG locations. For this purpose, threads were made on the T-shaped extension links to fine tune the location of the counterweights, which is also a novel contribution of this mechanism.

The prototype with counterweights was then mounted onto a bearing and then attached to a box. As illustrated in Figure 4, the orientation of the mechanism does not change if user releases the EE at any configuration, thus verifying the passive balancing of the mechanism.



(a) Orientation 1



(b) Orientation 2

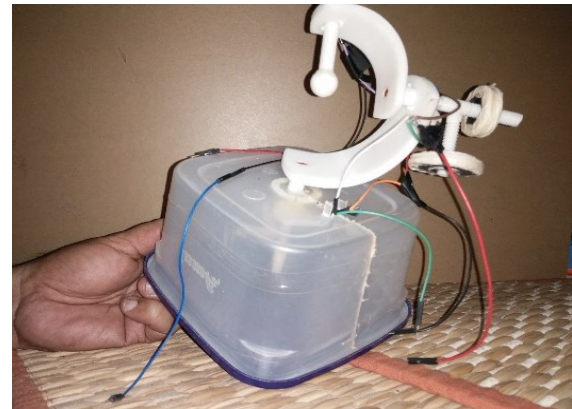


(c) Orientation 3 for Verification

Figure 3 - Hanging Method performed on Link2 and Link3 of the 3-ROSM



(a) Balanced in Orientation 1

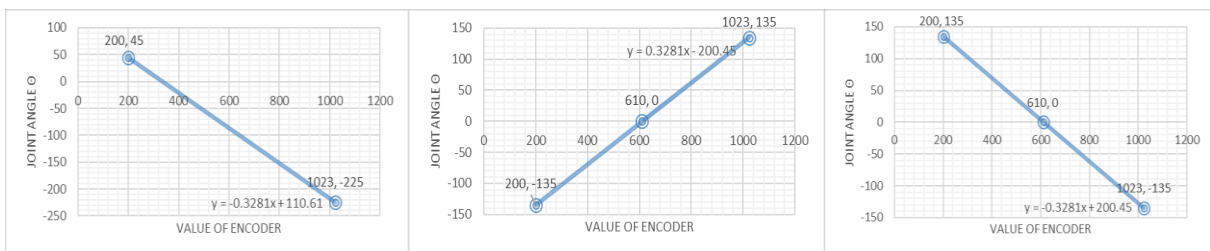


(b) Balanced in Orientation 2

Figure 4 - Passively Balanced prototype of the 3-ROSM

4. APPLICATIONS OF THE 3-ROSM

Hollow bore encoders by Tyco Electronics were used to measure the joint angles of the prototype. These have a voltage divider circuit in the form of a rotary potentiometer and the angle varies linearly with the output voltage. The encoders on the joint axis were connected to an Arduino microprocessor, which reads the value of the encoder (0 to 1023). The value was then mapped to give the corresponding angle of the corresponding joint. Each joint had a different mapping as the initial value and the way the encoder was attached was different, as illustrated in Figure 5. The encoders had a range of motion of 300° and in the prototype, only 270° motion was allowed through the usage of physical stoppers.



(a) Encoder for Joint 1

(b) Encoder for Joint 2

(c) Encoder for Joint 3

Figure 5 - Mapping of encoder value and joint angles

4.1. Motorized 3-axis camera mount

The prototype of the 3-ROSM was initially set to control the orientation of a 3-axis camera mount (Pan-Tilt-Roll) as a preliminary test of its controller capabilities. The movement of the joints of the camera mount is controlled by servo motors whose axes intersect with each other emulating the 3-ROSM i.e., this is a kinematically equivalent application because there exists a 1:1 mapping of the change in joint angle between the controller and the camera mount. The servo motors were actuated using the input data from the encoders, which is programmed using the Arduino software, as illustrated in Figure 5. The goal of this application was to obtain smooth transition of change in joint angles and to make it as intuitive as possible for the user. One of the challenges faced in this application was the limited range of orientation of the camera mount as the servo motors are constrained to a 180° rotation while the available rotation is 270°.

The camera mount and the orientation sensing mechanism prototype are shown in Figure 7. The camera was successfully controlled and once the user ceases to hold the EE of the orientation sensor, the camera's motion would also stop. Thus, controlling a camera on a 3-axis mount can be one of the applications of the proposed prototype.

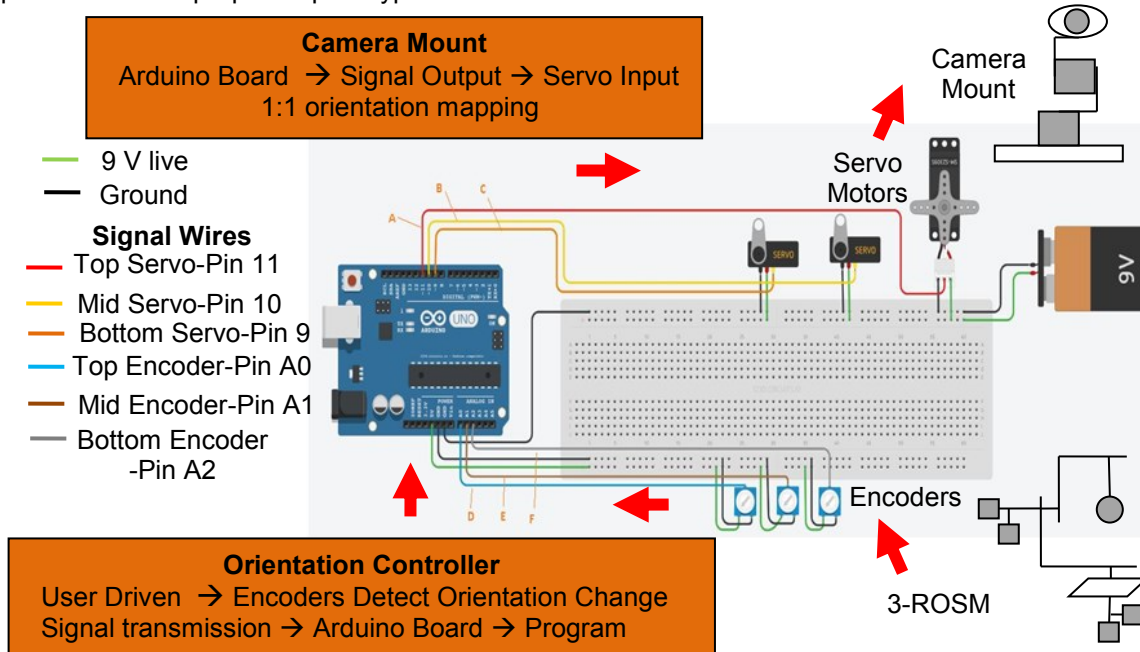


Figure 6 - Circuit diagram and flowchart for controlling a 3-axis camera mount using the 3-ROSM

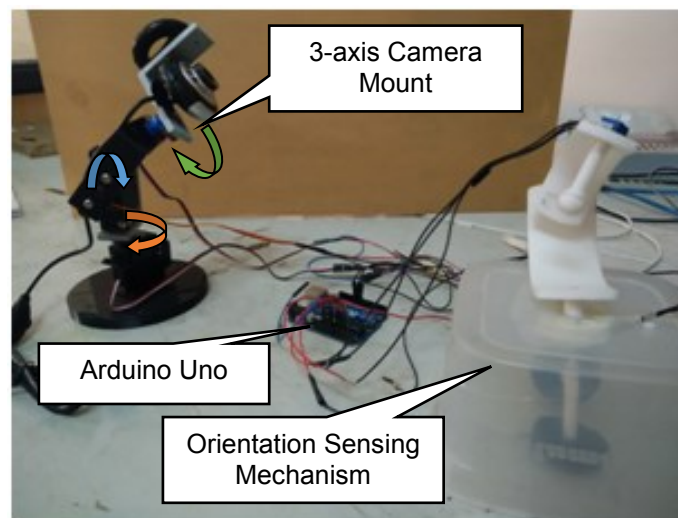


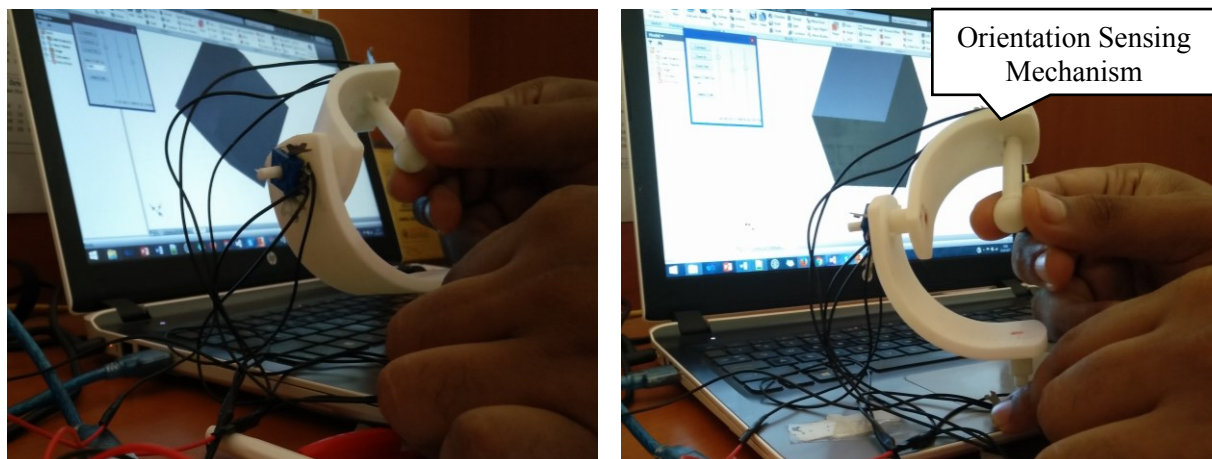
Figure 7 - Controlling a 3-axis camera mount using the 3-ROSM

4.2. Camera control in CAD software

CAD software with a 3D modelling capability has a provision to move the camera view around the object of interest in the virtual environment. This is typically achieved by using a mouse by the user. The camera location can be zoomed, panned and rotated such that an object can be viewed from a different position. The position and the orientation of the camera can also be controlled by using the proposed mechanism. Most CAD software have their API (Application Programming Interface) through which certain automation/customization can be done by developing programs.

Autodesk Inventor is one such CAD software whose API can be called using Visual C# programming language. Here, a C# Windows application was developed which received the joint angle information from Arduino through a USB interface. The angles received were used in Equation (1) to determine the orientation of the EE of the mechanism. The orientation of the EE was mapped to the camera in the CAD software such that there was a 1:1 mapping between the motion of the EE and that of the camera in the CAD software. Using the API, the camera location and orientation was modified according to the joint angles received.

Images of two different orientations of the input device and the corresponding camera configuration in the CAD software are shown in Figure 8. The control of the camera location was found to be intuitive and thus, the proposed mechanism can be used to intuitively control the camera motion in a CAD software.



(a) Camera viewing from one camera position (b) Camera viewing from another camera position

Figure 8 - Controlling configuration of camera in CAD software using the 3-ROSM

5. CONCLUSIONS

The authors have developed a prototype of the 3-ROSM and presented its applications in this paper. The device has encoders placed at its joints and by measuring the joint angles, the orientation of an object, both physical and virtual, can be changed accordingly. The device also has passive gravity balancing capabilities, thus requiring lesser effort to use and is also apt for applications where the orientation of the object has to be controlled and should not change once the user stops controlling it. The developed prototype was used to successfully control a 3-axis camera mount and also to move the camera around in a CAD software environment.

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