Passive Balancing of a Novel 3-R Orientation Sensing Mechanism

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ABSTRACT

A lot of applications require controlling the orientation of an object and this can be achieved using mechanical input devices or mechanisms with electronic sensors. It is desired that these mechanisms are balanced, such that they retain their orientation even after the user has stopped using it. This can be achieved using active or passive balancing techniques. A passively balanced mechanical input device utilizes springs or/ placement of optimum masses at appropriate distances such that the overall forces and moments acting on the mechanism are balanced. As the configuration of the links change according to the user's input, the mechanism should be designed such that the overall centre of mass remains constant. In this paper, a novel 3-R Orientation Sensing Mechanism (3-ROSM) is presented, which consists of three moving links and one fixed link. The characteristic feature of this mechanism is that the three axes of the links are intersecting as found in various gimbal linkage systems. The balancing is carried out using counterweights placed on linkages on the moving links. The end result is a mechanism that can be used as a hand operated balanced mechanism (HOBM) in applications such as tele-surgery; control of a CCTV camera mounted on a gimbal mechanism, etc., which utilize master-slave robotics as a principle. The proposed mechanism has been modelled and simulated for dynamic analyses in a CAD software and found to be suitable for passive balancing.

Keywords: gravity compensation, passive balancing, orientation sensor, orientation mechanism.

1. INTRODUCTION

A serial robot can be used to perform tasks that are defined in the Cartesian space, whereas the joints or actuators of the robot are generally controlled in the joint space. These robots can be controlled using devices such as teach pendents or through offline-programming performed using a computer. The teach pendents, typically used to move a robot has buttons which increment or decrement the values of the robot joints or move the robot in the Cartesian space directly along the principal directions. However, the method of pressing buttons to achieve motion is not very intuitive as the user has to relate buttons and their resulting action. Since most of the serial robots used in industries are 6-axis robots which have last three axes intersecting at a point, known as the wrist of a robot. The first three joint axies can be actuated to control the position of the gripper attached to the last link, known as the end-effector. The last three joint axes can be actuated to control the orientation of the end-effector. Hence, the position and orientation can be decoupled for easier control.

For intuitve control of a robot, it is best to have two different input devices. A mechanism which allows translation along three orthogonal axes can be used to control the position of the end-effector. An example mechanism is a delta mechanism with three DOFs such as Novint Falcon, which is a commercially available device. For the control of orientation, an input device which has intersecting axes would be ideal and more intuitive. An overview of several input devices and mechanisms are discussed in [12]. Apart from robots, several other applications exist where the control of orientation is required. For example, controlling a three-axis camera used for CCTV operations. For both position and orientation sensing mechanisms or manipulators, it is important for the mechanism to be balanced such if the mechanism is let off, it would return to its most stable configuration under the action of gravity. Therefore, the balancing of mechanisms is desired such that their configuration does not change after the last use. The two types of balancing considered are active balancing and passive balancing. Active balancing makes use of external actuators which may be electric, hydraulic or pneumatic in nature. Passive balancing utilizes compensation inertia or springs. Since the external actuators are not required in passive balancing, it is more economical, simple and energy efficient compared to active balancing [16].

Another aspect of passive balancing is that it can be achieved either through static or dynamic Balancing. As explained in [7], A mechanism is statically balanced when the weight of the links does not produce any resultant moment at the point of consideration (e.g. Joints) under static conditions, i.e., the potential energy of the mechanism is constant for any configuration of the mechanism. “A mechanism is said to be dynamically balanced if, for any motion of the mechanism, there is no reaction force (excluding gravity) and moment on its base at all times” as defined in [8]. Passive balancing in many applications has been accomplished by the use of springs [4]. Springs, that may be linear or non-linear in nature are used as they do not supply any excess or undue energy to the system under consideration. These springs store the energy supplied to them by virtue of the mechanism orientation and utilize this stored energy to retain the configuration of the manipulator either under static or dynamic conditions.

An alternative method to achieve static balancing is the usaage of counterweights which maintain the mechanism's constant centre of mass due to redistribution of mass of the links. Counterweight balancing appears to be preferred over spring balance as any additional mass on links such as encoders, etc. can be compensated by varying the countermasses or the position of the countermasses. The concept is also much simpler and since the mechanism would have low inertia, the overall increase in inertia of the manipulator would not cause for concern. Certain guidelines are explained in [14]. Counterweight balancing has already been proved to be efficient in many practical applications such as in the field of medical sciences [5] and [9]. There are also various advances in counterweight balancing with respect to design of robot arms as shown in [10] and [15]. Counterweight balancing need not necessarily mean the addition of external weights. In [6], the design of the link member, which happens to be a beam, is done such that the mass distribution balances the overall torsion acting on the joints.

In this paper, a novel 3-R Orientation Sensing Mechanism (3-ROSM) is proposed, which can be used to control orientation of any robot or other similar devices. It consists of three movable links and a fixed links. These four links are connected using three revolute joints in series, such that the axes of all these joints intersect at a point. The geometric construction of the mechanism is discussed in Section 2, followed by the description of the passive counterweight balancing method in Section 3. Simulation was performed for dynamic analysis on the mechanism and the results are reported in Section 4. A work-in-progress prototype developed by the authors is breifed in Section 5, followed by the conclusions.

2. ORIENTATION SENSING MECHANISM

The mechanism proposed has three moving links (Link1, Link2 and Link3) and a fixed link (Link0) connected in series using revolute joints as shown in Figure 1.

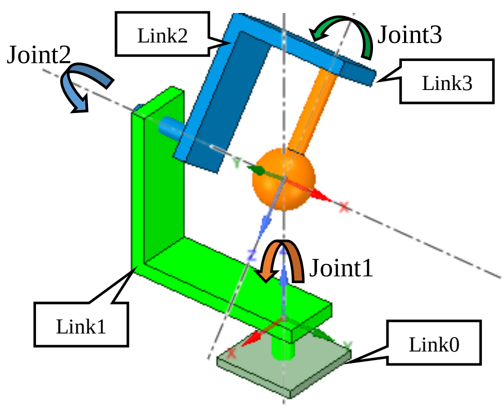


Figure 1: CAD model of 3-ROSM

As the mechanism has three revolute joints, it is named as 3-ROSM (3-Revolute Orientation Sensing Mechanism). The axes of the joints Joint1, Joint2 and Joint3 intersect at a point, similar to a wrist of a 6-axis wrist-partitioned robot. The last link, i.e., Link3 has a spherical shaped object, referred as the end-effector (EE), which can be held by the user to change the configuration. When the user tries to move the EE, the center of the sphere remains at the same position, as the three axes intersect for any configuration of the mechanism. The only thing that changes is its orientation of the EE, with respect to the fixes link (Link0).

Like in serial robots, the architecture of the proposed serial mechanism can be represented using the Denavit-Hartenberg (DH) parameters. Four parameters are used to represent the position and orientation, collectively known as configuration, of the DH coordinate frame attached on a link, with respect to the DH coordinate frame attached on the previous link. A brief explanation of these parameters is given in Table 1 and illustrated in Figure 2. The nomenclature and methodology described in [11] is followed in this paper, where more details about the procedure on DH parameters assignment can be found.

Table 1. Description of DH parameters

Parameter	**Description**
Joint offset (b_i)	Distance between X_i and X_{i+1} along Z_i
Joint Angle (θ_i)	Angle between X_i and X_{i+1} about Z_i
Link Length (a_i)	Distance between Z_i and Z_{i+1} along X_{i+1}
Twist Angle (α_i)	Angle between Z_i and Z_{i+1} about X_{i+1}

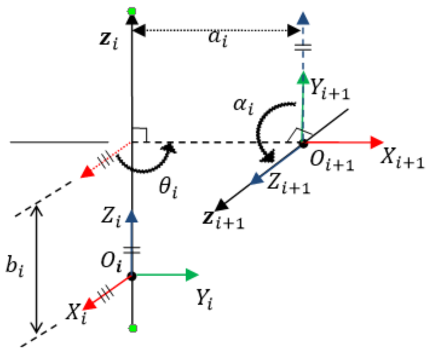


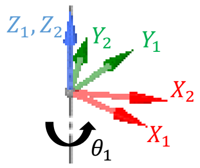
Figure 2: DH parameters between Framei and Framei+1

A Homgoeneous Transformation Matrix (HTM) is used to represent the configuration between two DH coordinate frames. For example, the HTM between Frame$_{i+1}$ with respect to Frame$_i$ is given by

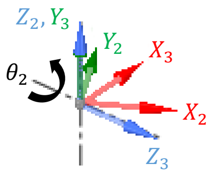
$$\mathbf{T}_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & b_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

As the position of the EE of 3-ROSM remains invariant, the DH coordinate frame attached to the fixed link (Link0) can be assumed to be at the center of the spherical EE, such that the Z axis, i.e., Z_1, of Frame$_1$ (attached to Link0) is along the direction of the axis of Joint1, as shown in Figure 3(a). The X axis of Frame$_1$, i.e., X_1, can be taken arbitrarily. Y_1 axis is computed as a cross-product between the Z_1 and X_1 axes. As per the DH parameter convention, the DH coordinate frame, Frame$_2$, attached to Link1 has to be located such that Z_2, is along the axis of Joint1. This makes Z_1 and Z_2 collinear and hence the origin of Frame$_2$ (O_2) has to be along Z2. Though there exist infinite number of points on the axis of Joint1, where O2 can be located, it is coincided with O_1, to simplify the resulting mathematical expression. X_2 can be chosen arbitrarily such that it is orthogonal to Z_2, and Y_2 can be found using cross-product rule. Of the four DH parameters; joint offset (b_1), link length(a_1) and twist angle (α_1) are all zero. The only variable is joint angle

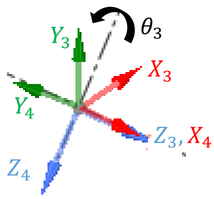
(θ_1) which is the angle between X_2 and X_1, which changes as Joint1 is rotated. The HTM of $Frame_2$ with respect to $Frame_1$ can be determined using the expression given in Figure 3(b).



(a) Frame1 and Frame2



(c) Frame2 and Frame3



(e) Frame3 and Frame4

$$\mathbf{T}_1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(b) HTM of Frame2 with respect to Frame1

$$\mathbf{T}_2 = \begin{bmatrix} \cos\theta_2 & 0 & \sin\theta_2 & 0 \\ \sin\theta_2 & 0 & -\cos\theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(d) HTM of Frame3 with respect to Frame2

$$\mathbf{T}_3 = \begin{bmatrix} \cos\theta_3 & 0 & \sin\theta_3 & 0 \\ \sin\theta_3 & 0 & -\cos\theta_3 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(f) HTM of Frame4 with respect to Frame3

Figure 3: DH frames attached to the links of the mechanism

Once $Frame_2$ is completely determined, $Frame_3$ (attached on Link2) has to be found. Z_3 has to be along axis of Joint2. Since Z_2 and Z_3 intersect, origin of the frames $Frame_2$ and $Frame_3$ coincide. As X_3 has to be perpendicular to both Z_2 and Z_3, it can be obtained as $Z_2 \times Z_3$ (though $Z_3 \times Z_2$ can also be taken). Y_3 can be obtained using cross-product rule. Of the four parameters between frames $Frame_2$ and $Frame_3$, joint offset (b_2) and link length (a_2) are zero due to intersecting joint axes. The joint angle (θ_2) is a variable, i.e., the angle between X_2 and X_3, which changes when Joint2 is rotated. The fourth parameter, twist angle (α_2) is 90°, since Z_2 and Z_3 intersect orthogonally, due to the virtue of the construction of the mechanism. $Frame_2$ and $Frame_3$ are illustrated in Figure 3(c) the corresponding HTM is given in Figure 3(d).

Similarly, Joint2 and Joint3 intersect as shown in Figure 3(e) and the HTM is given in Figure 3(f). The DH parameters for the entire mechanism is given in Table 2.

Table 2. DH parameters of orientation sensing mechanism

Parameter / Joint	Joint offset (b_i)	Joint Angle (θ_i)	Link Length (a_i)	Twist Angle (α_i)
Joint1	0	θ_1 (variable)	0	0°
Joint2	0	θ_2 (variable)	0	90°
Joint3	0	θ_3 (variable)	0	90°

The HTM of Frame4 with respect to Frame1 is determined by multiplying the individual HTMs as

$$\mathbf{T} = \mathbf{T}_1\mathbf{T}_2\mathbf{T}_3 = \begin{bmatrix} \cos(\theta_1+\theta_2)\cos\theta_3 & \sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2)\sin\theta_3 & 0 \\ \sin(\theta_1+\theta_2)\cos\theta_3 & -\cos(\theta_1-\theta_2) & \sin(\theta_1-\theta_2)\sin\theta_3 & 0 \\ \sin\theta_3 & 0 & -\cos\theta_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

This HTM has two primary components. The elements in the first three rows and three columns correspond to the orientation between $Frame_4$ and $Frame_1$, representing the direction-cosines. These elements are a function of joint angles of Joint1, Joint2 and Joint3. The elements in the fourth column and first three rows correspond to the position of the origin of Frame4 with respect to that of Frame1. Note that all the elements are zero and are independent of the joint angles. Hence, the proposed mechanism can be used as a Orientation Sensing Mechanism.

3. GRAVITY BALANCING OF MECHANISM

The mechanism discussed in Section 2 can be used for orientation measurement. However, if the user stops acting on the mechanism, it would orient itself due to the action of gravity and reach its most stable configuration. For the orientation not to change, gravity compensation has to be performed either using active or passive balancing techniques. As mentioned in Section 1, passive techniques are preferred as they are simple and inexpensive. In passive balancing, springs or counterweights can be used. In the literature [2], a term 'Hand Operated Balanced Mechanism (HOBM)' is used which is defined as "handling system with a simple mechanical actuator in which the manipulated object in any position of the workspace is also balanced". The concepts of the HOBM, explained in [3], have already been applied to the field of manufacturing, to be precise, in moving heavy objects manually. Another example [13] describes the research on linking a robot capable of performing surgery by a surgeon at a remote location. HOBM mechanisms can be used so that the surgeon has a certain familiarity in handling the robot. To further develop this familiarity, dynamic and static balancing enable a finely tuned manipulator to accomplish tasks such that the surgeon feels immersive during the surgery.

In this section, passive balancing of the proposed mechanism using counterweights is discussed, which can also be classified as a HOBM. As described in [1], there are two principal subgroups in counterweight balancing. It can be achieved by mounting counterweights on the links of the initial system or by mounting counterweights on auxiliary linkages connected with the initial system. An auxiliary link is any mechanical structure that is mounted between the balancing element and the initial structure of the manipulator. The former is generally used in serial robots and planar parallel robots. The latter is generally used in spatial parallel robots and is generally complex than the former.

3.1. Modifications in Links

In the proposed mechanism, the gravity compensation is achieved by placing counterweights on the links of initial system, but after having a T-shaped extension in two of the moving links, as illustrated in Figure 4. Note that Link3, which has a spherical EE is symmetric about the axis of Joint3. Hence, for any rotation (θ_3), the Center of Gravity (CG) of Link3 is always along the axis of Joint3 and hence Link3 is balanced. Link2 is extended to have a T-shape in the direction opposite to its original shape. The extended link would have its CG away from the axis of Joint2. The CG of Link3 can be considered as an extra mass added on Link2, as the CG of Link3 does not change with respect to Link2. For the combined Link2(with extension) and Link3, counterweights can be added along the T-shaped extension so as to balance about the axis of Joint2. Now that Link2 and Link3 are balanced for any θ_2 rotation, the combined masses of Link3, Link2 and the counterweights on Link2 can be assumed to be fixed on Link1. Similarly, a T-shaped extension on Link1 can have counterweights such that the combined CG of all the Links and counterweights lies along the axis of Joint1 and hence is balanced for any θ_1 rotation.

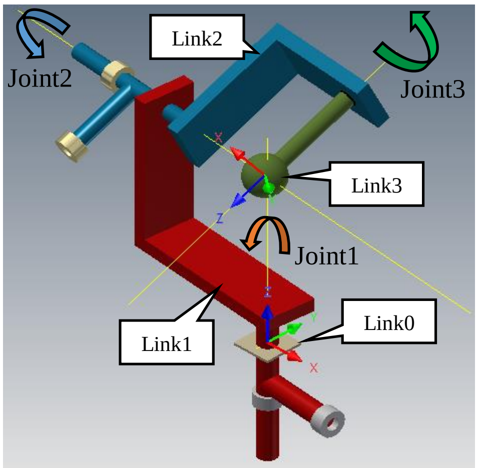
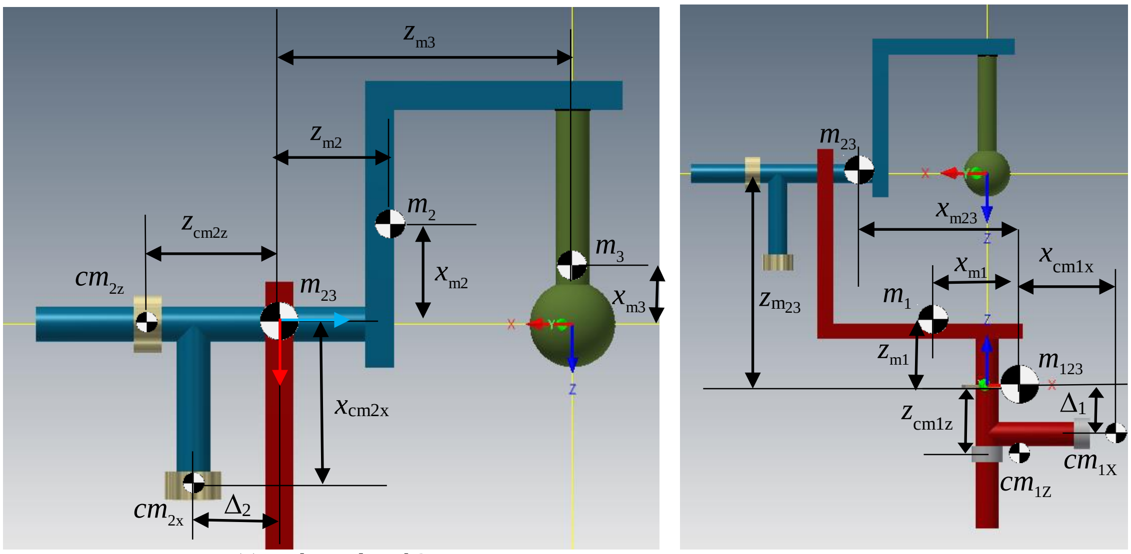


Figure 4: Counterweights on 3-ROSM

The novelty in this mechanism is the T-shaped extension to hold the counterweights, as it gives two orthogonal directions to adjust the placement of counterweights. The counterweights can be calculated as described next. However, with time or with addition of extra masses on the links, the balancing gets disturbed. By moving the counterweights along the orthogonal extensions, the modified system can be easily balanced.

3.2. Balancing of Link2 and Link3 Along Joint2 Axis

Referring to Figure 5(a), consider the masses of Link3 as m_3 and of Link2 as m_2. Let the countermasses be cm_{2z} along the Z axis (axis of Joint2) and cm_{2x} along the X axis (transverse direction). Different length parameters used for calculations are as shown in the firgure.



(a) Link2 and Link3 (b) All links

Figure 5: Balancing of 3-ROSM mechanism using counteweights

It is desired that the effective CG of the two links and the counterweights coincide at the support point for Joint2 on Link1, represented using m_{23}. This is achieved by equating the moments about the Z and X axes, respectively, as

$$(m_2 \cdot x_{m2}) + (m_3 \cdot x_{m3}) = (cm_{2x} \cdot x_{Cm2x}) \tag{3}$$

$$(m_2 \cdot z_{m2}) + (m_3 \cdot z_{m3}) = (cm_{2z} \cdot z_{Cm2z}) + (cm_{2x} \cdot \Delta_2) \tag{4}$$

The primary principle used in the counterweight balancing of the 3-ROSM is that the mass of the counterweights are fixed and only the distances are varied. From Equations (3) and (4), the distances c_{m2x} and c_{m2z} can be determined.

3.3. Balancing of all Links Along Joint1 Axis

Since the combined mass of Link2, Link3, cm_{2x} and cm_{2z} is invariant in the plane containing axes of Joint1 and Joint3. These masses can be replaced by mass m_{23} on Joint2, as shown in Figure 5(b). For the gravity balancing along Joint1 axis, the combined mass of m_{23} and m_1 are balanced by counter masses cm_{1x} and cm_{1z} placed on the sliders on Link1, such that the combined mass of all the links and counter masses (m_{123}) is on axis of Joint1. The coordinates x_{cm1} and z_{cm1} for the placement of counter masses can be obtained using

$$(m_{23} \cdot x_{m23}) + (m_1 \cdot x_{m1}) = (cm_{1x} \cdot x_{Cm1x}) \tag{5}$$

$$(m_{23} \cdot z_{m23}) + (m_1 \cdot z_{m1}) = (cm_{1z} \cdot z_{Cm1z}) + (cm_{1x} \cdot \Delta_1) \tag{6}$$

4. CAD SIMULATION AND PROTOTYPE DEVELOPMENT

To test the theory upon which the 3-ROSM was designed, a prototype of the 3-ROSM was developed. Instead of using links with rectangular cross-section, the prototype was made using PVC pipes. As various solutions, such as T-joints and elbow bends were readily available to provide joints, working with PVC pipes decreased the complexity of the design. Since the materials were commercially available, uniformity in density of the pipes was assured as opposed to working with hand crafted links which would have affected the accuracy of the mass and centre of mass calculations.

A CAD model of the 3-ROSM prototype was created for the specifications of the PVC pipes and the PVC accessories in Autodesk Inventor CAD software. The CAD model is shown in Figure 6. The centre of mass was calculated in the software by inputting the measured values of masses of the various components of the mechanism and measuring the distance of the centre of mass from the point of consideration (which is Joint2 first and then proceeding to Joint1).

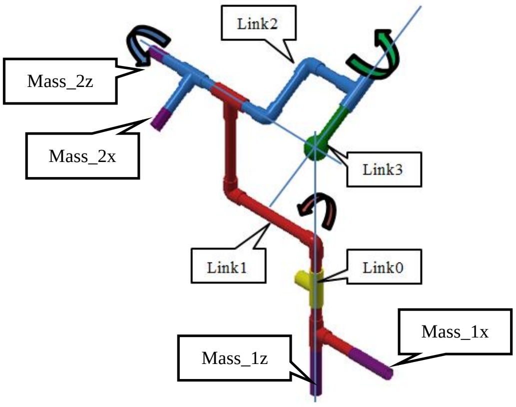


Figure 6: CAD model of a 3-ROSM prototype

These values were plugged into Equations (3-6), after fixing suitable masses for the counterweights. The locations of the counterweights from the point of consideration were calculated from the equations. The masses of the counterweights may be increased or decreased if the displacement is found unrealistic as compared to the lengths of the extended links. The locations of counterweights that were measured for the virtual prototype are tabulated with their respective masses in Table 3.

Table 3. Details of the 3-ROSM parameters and counterweights location

Link/counterweight	Link Mass (grams)	Location of CG in with respect to Link1 or Link2	
		X axis (mm)	Z axis (mm)
Link1	m_1 = 452.00	x_{m1} = 91.930	z_{m1} =75.913
Link2	m_2 = 232.00	x_{m2} = 59.570	z_{m2} = 54.356
Link3	m_3 = 35.00	x_{m3} = 233.000	z_{m3} = 87.000
Mass_2x	cm_{2x} = 35.00	x_{mc2x} =195.000	0.000
Mass_2z	cm_{2z} = 150.00	0.000	z_{mc2z} =104.377
Mass_1x	cm_{1x} = 900.00	x_{mc1x} =149.114	0.000
Mass_1z	cm_{1z} = 400.00	0.000	z_{mc1z} =191.812

The counterweights were placed in the CAD model at determined locations and 'Dynamic Simulation' module of Autodesk Inventor was used to simulate the action of gravity on the mechanism. It was observed that the mechanism remained intact and did not move for any configuration of the mechanism. The virtual experiments were tested for different configurations of assembly and also by setting the direction of gravity to be arbitrary. Thereby, the proposed gravity balancing technique was validated in a CAD environment.

4.1. Physical Prototype

A physical prototype of the mechanism was developed, based on the location of the counterweights obtained from CAD simulation. The balancing about Joint3 was obtained as Link3 was axis-symmetric. Balancing about Joint2 was done with minor adjustments of the counterweights location, as there were some descripencies between the CAD model and actual model. Balancing about Joint1 was attempted but could not be obtained. The prototype with Joints2 and Joints3 are shown in Figure 7.

Figure 7: Physical prototype of 3-ROSM

5. CONCLUSIONS

A novel mechanism to measure orienation has been presented in this paper. The mechanism, 3-ROSM, has been passively balanced using counterweights such that the mechanism retains its orientation after its use. The proof of concept was verified by the construction of a CAD model in Autodesk Inventor sotware. The authors note that the proposed mechanism has a singularity when the axes of Joint1 and Joint3 are aligned, and it must be avoided. A physical prototype involving Link2 and Link3 at Joint2 was constructed using PVC pipes and specially designed counterweights. This physical prototype was statically balanced, thus validating the concept. The authors acknowledge the presence of a very small factor of friction that could affect the accuracy of the prototype, requiring minor adjustments in the location of counterweights.

Future work regarding the development of the 3-ROSM would include the completion of the entire physical prototype and achieving passive balancing at Joint1 with respect to all the Links. Also, to measure the joint angles in the mechanism, encoders will be added on each of the three joints. The measured angles will be used to determine the orientation of the end-effector (EE), which can be used for various applications where orientation is to be controlled.

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