Modeling Contact Interaction of a Hand Prosthesis with Soft Tissue at the Interface*

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Abstract - *It is interesting to study the phenomenon of contact interaction with an object and its manipulation using prosthetic mechanisms proposed earlier by the authors. The task is made challenging due to the presence of soft fingertips, and the combined action of sliding and rolling at the contact interface. Detailed Bond graph modeling of the contact phenomenon for one and two degrees of freedom of the prosthesis is presented. Effects due to softness of the fingertips while manipulating an object, extensibility of actuation strings and their internal damping, bearing friction at joints, etc., which are encountered in the prosthetic system, are modeled.*

Keywords: Prosthesis, robot hands, soft fingertips, Bond graphs, modeling, simulation.

1 Introduction

The authors have recently proposed a simple but extremely useful design concept for the actuation of prosthetic fingers for a partially deformed human hand [3]. The design uses the ability of the remaining natural fingers to provide movement capability to the prosthetic fingers on the same hand. The concept has been successfully demonstrated for actuation of single and two degrees of freedom (DOF), and can be easily extended for multiple DOF. The proposed mechanism can be used to design configurations which perform practically most of the functional tasks carried out by human hands as mentioned in [13], [7]. It also results in reduction of DOF, a feature which makes it simple to implement. It can be used effectively and made more versatile by further incorporating soft fingertips [8], [12] or tissue to perform a large category of essential daily tasks.

A prosthetic mechanism for a hand, which has lost a thumb but retains the abilities of the other remaining fingers, was developed as an example to demonstrate the proposed design [3]. The mechanism incorporates merely 2 DOF at the rigid skeletal level. The prosthesis is therefore very affordable and simple, and holds great promise for persons with such prehensile disabilities.

It is interesting to study the phenomenon of contact with an object and its manipulation using this prosthetic mechanism. The task is made challenging due to the presence of soft fingertips, and the combined action of sliding and rolling at the contact interface. Efforts to model rolling effects of contact interaction have been in progress since the 1980s [6]. The modeling of contact interactions with acatastatic nonholonomic constraints has been presented in [10], where rolling contact with rigid bodies has been considered. Detailed description of manipulation with rolling contacts with rigid objects can be found in [11]. Detailed modeling of the contact phenomenon for 1 and 2 DOF are presented. Although this seems restrictive, it still includes a large category of useful tasks like holding, twitching, fine positioning, etc., for the prosthesis.

Bond graph modeling is used to represent system dynamics of the proposed system [5], [2]. This is an intentional attempt to explore the modeling intricacies encountered in the system, using an alternative but powerful modeling technique. Bond graphs represent the dynamics of a system pictorially, and are extensively used for the modeling of physical system dynamics in multiple energy domains. A Bond graph model is based on the interaction of power between the elements of the system. Cause-effect relationships are also depicted and help in deriving the system equations in an algorithmic manner. Further, the model yields insight into various aspects of control of the system [2].

Effects due to softness of the fingertips while manipulating an object, extensibility of actuation strings and their internal damping, bearing friction at joints, etc., which are encountered in the prosthetic system, are modeled using Bond graphs.

A brief review of the principles of the basic wire based prosthetic mechanism is offered in the next section. Bond graph models for one and two-joint actuated prostheses are presented in the third section, which is followed by conclusions.

2 Principle of the basic mechanism: a brief review

We shall briefly review the working of the mechanism as required for development of its dynamic model. Details of the working of the mechanism are available in [3] and are not repeated here.

Consider the mechanism in Figure 1. It consists of two links, the left one representing the thumb, a passive link in this case, and the right one representing a link attached to an active finger, say the index finger. Both these links are considered to be hinged on a third rigid link at ***L*** and ***R*** respectively. Two strings, almost inextensible, are used for actuation of the prosthetic thumb joint. The strings are required to be taut always. A string can actuate a finger link while it is in tension only. The strings can be passed through sheath tubing as in the case of bicycle brake wires. This can ensure constant string length between the pulleys, while maintaining appropriate string tension, even if the center distance ***LR*** changes. Further, the axes of rotation about ***L*** and ***R*** need not be parallel nor fixed.

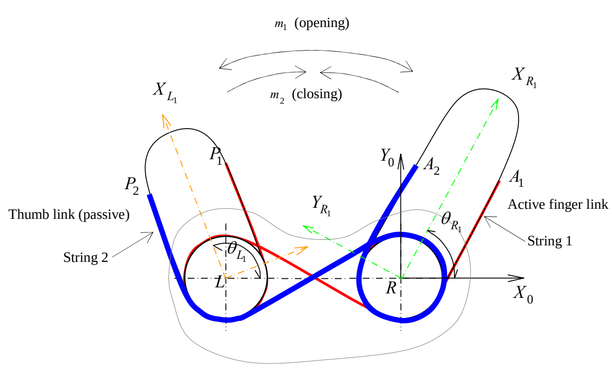
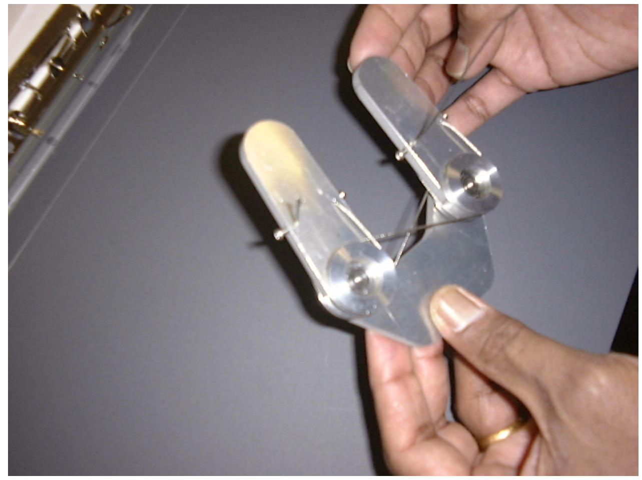


Figure 1. A two-finger mechanism actuated by strings. In this case, only one joint is actuated (active) and the other joint is passive.

Movement of the active finger link results in a corresponding movement of the passive finger link, in the opposite sense.

The principle shown in this mechanism can be extended to the actuation of more joints. The advantage is that the axes of the joints need not be parallel or fixed. This has been shown in a later subsection of this paper. Pictures of the one and two-joint actuated prosthetic mechanisms are shown in Figure 2.



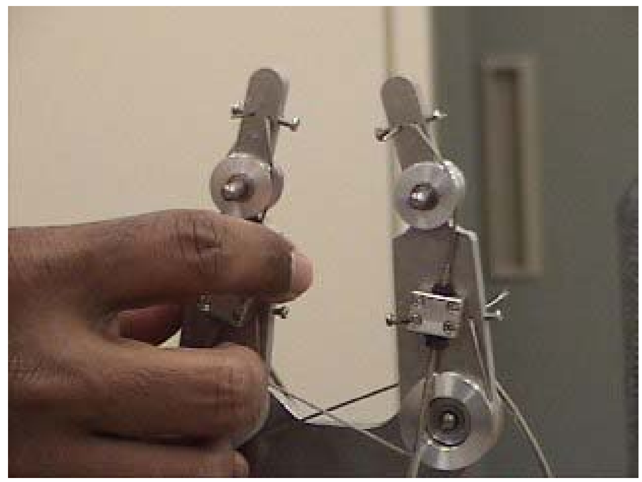


Figure 2. Photographs of the prosthesis (a) one joint actuated. (b) two joint actuated.

3 Bond graph modeling of the proposed prosthetic mechanisms

Models of the dynamics of these prosthetic systems can help analyze, simulate and understand the detailed working of the mechanism during its operation. In the following subsections we present the application of Bond graph modeling to a one-joint actuated prosthesis, referred also as 1 DOF prosthesis, and a two-joint actuated prosthesis, also referred to as 2 DOF prosthesis. Details about this method of modeling, and the art of constructing Bond graphs can be found in [5] and [2].

3.1 Model for the one joint actuated prosthetic system

The prosthesis of Figure 1 can be used to manipulate objects as done by human fingers (Figure 3).

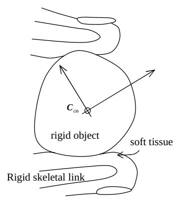


Figure 3. Soft contact manipulation with human fingers

The effect of contact with an object, as in Figure 3, is included in the model.   shows the Bond graph for the system of Figure 1.

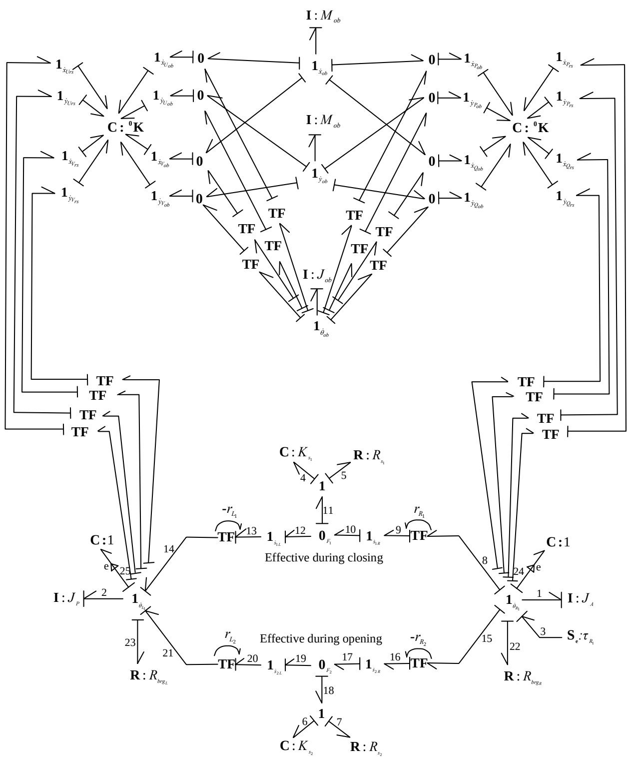


Figure 4. Bond graph of the prosthetic system showing soft contact with a rigid object

Junction $1_{\dot{\theta}_{R_1}}$ represents the common flow variable $\dot{\theta}_{R_1}$. $S_e : \tau_{R_1}$ is the element showing the effort variable, torque τ_{R_1}, applied at junction $1_{\dot{\theta}_{R_1}}$, as a result of movement of the active finger. The rotary inertia of the active finger link, about the joint R, is modeled by $I : J_A$ in the Bond graph. J_A is the moment of inertia of the active link about the axis at R, normal to the plane. The string 1 on the active finger link is pulled and a force due to string tension is experienced at A_1, along the string. This force of magnitude F_{A_1}, is along the $-\hat{x}_{R_1}$ direction, and is represented by the $0_{F_{A_1}}$ junction. The transformer element $TF : r_{R_1}$ relates this force to the moment it generates about the joint R. Due to its power conserving nature, it also relates the angular velocity component $\dot{\theta}_{R_1}$ to the speed of winding of the string $\dot{s}_1$. Under the assumption that no force is lost in transmission, the string applies this force at point P_1 on the passive thumb link. This results in the development of a moment about joint L and consequently in the movement of the passive thumb. Junction $1_{\dot{\theta}_{L_1}}$ represents the common flow variable $\dot{\theta}_{L_1}$. The rotary inertia of the passive finger link, about the joint L, is modeled by $I : J_P$. Two paths have been shown in the Bond graph between the $1_{\dot{\theta}_{R_1}}$ and $1_{\dot{\theta}_{L_1}}$ junctions. These are on account of the two strings 1 and 2.

During the opening movement, the index finger is moved outwards. θ_{R_1} decreases, and a moment τ_{R_1} is applied about joint R in the direction m_1. The string 2 on the active finger link is pulled and a force due to string tension is experienced at A_2, along the string. This force is represented by the junction $0_{F_{A_2}}$. The radius of the base pulley at R for string 2 can be different, and has been shown intentionally to be so, using the transformer element $TF : -r_{R_2}$, which depicts the relationship between the force and the moment generated by it. It also relates the angular velocity $\dot{\theta}_{R_1}$ to the speed of winding of the string $\dot{s}_2$. Note the difference of the signs between the transformer moduli in the two cases. The forces F_{A_1} and F_{A_2} act on strings 1 and 2 respectively.

Modeling of the soft material using Bond graphs for the planar case has been explained in [4] and only a brief review is presented here. Consider the object being held by the hand prosthesis as shown in the Figure 3. A layer of soft material is shown between the object and the rigid link. It is bonded to the surface of the rigid link at the soft material-rigid link interface. Contact mechanics involved in grasping and rolling of objects has been considered in literature. The manipulator fingers and the object are usually considered as rigid bodies. In manipulation with human hands, the situation seems to be somewhat different. The fingers are part of a rigid skeletal structure, which can be considered as a rigid mechanism. Between the object, which is grasped and manipulated, and the fingers, is flesh and skin, which may be considered as soft tissue material.

The material is fixed on one side to the skeletal structure of the fingers, and is covered by the skin on the other side which manipulates the object. This allows for slipping, non-slipping, releasing, etc. at the *object-soft material* interface. Unlike contact between rigid bodies, in this case an area of contact develops, both at the *object-soft material*, and *soft material-rigid skeletal link* interfaces. These surface areas are unknown and can change during the manipulation. The net force at the interface can be considered to be distributed over points on the respective surface areas.

Since the system is considered to be planar, only the variables θ_{Ob}, ${}^{0}_{0}x_{C_{Ob}}$, and ${}^{0}_{0}y_{C_{Ob}}$ are essential to model the dynamics of the rigid object. The corresponding velocities are shown by junctions $1_{\dot{\theta}_{Ob}}$, $1_{{}^{0}_{0}\dot{x}_{C_{Ob}}}$, and $1_{{}^{0}_{0}\dot{y}_{C_{Ob}}}$ respectively. The soft material is viewed as a Bond graph C-field. It relates the forces acting on the rigid link and rigid object surfaces at an interface. The forces are based on the deformation of the soft material during contact. The deformation is related to the motion of points on the contact surfaces at the *object-soft material*, and *soft material-rigid skeletal link* interfaces. A simple consideration of the soft material stiffness is as follows. During contact, a soft material fiber may be considered as a line or curve connecting a point on the *object-soft material* interface with a point on the *soft material-rigid skeletal link* interface. Points on the *soft material-rigid skeletal link* interface are considered to be fixed as the material is bonded on the rigid skeletal link. However, relative motion between points on the object surface and soft material surface is possible at the *object-soft material* interface, if slipping occurs. A fiber $\boldsymbol{P}$ connects points $\boldsymbol{P}_{rs}$ and $\boldsymbol{P}_{Ob}$ on the rigid link end and the object end respectively.

The effort vector due to deformation of the fiber $\boldsymbol{P}$ is given by

$${}^{0}\overline{\mathbf{F}}_{P} = \begin{Bmatrix} {}^{0}\overline{F}_{P_{rs}} \\ {}^{0}\overline{F}_{P_{Ob}} \end{Bmatrix} = {}^{0}\mathbf{K}_{P}\left\{ {}^{0}_{0}\overline{\mathbf{r}}_{P} - {}^{0}_{0}\overline{\mathbf{r}}_{P_{in}} \right\} \qquad (1)$$

which is the C-field relationship for fiber $\boldsymbol{P}$. The stiffness matrix expressed in the frame $\boldsymbol{0}$ is obtained from that expressed in frame $\boldsymbol{R}_1$ as

$${}^{0}\mathbf{K}_{P} = {}^{0}_{R_1}\mathbf{R}_{4}\ {}^{R_1}\mathbf{K}_{P}\ {}^{0}_{R_1}\mathbf{R}_{4}^{T} \qquad (2)$$

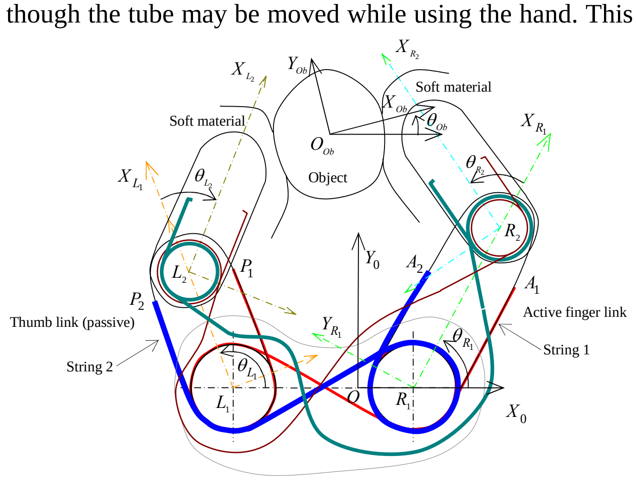
It is easier to specify the stiffness matrix in the frame $\boldsymbol{R}_1$. The position vectors of points at the ends of the fiber $\boldsymbol{P}$ are composed in one vector

$${}^{0}_{0}\overline{\mathbf{r}}_{P} = \begin{Bmatrix} {}^{0}_{0}\overline{r}_{P_{rs}} \\ {}^{0}_{0}\overline{r}_{P_{Ob}} \end{Bmatrix}. \text{ Also, } {}^{0}_{0}\overline{\mathbf{r}}_{P_{in}} = \begin{Bmatrix} {}^{0}_{0}\overline{r}_{P_{rs_{in}}} \\ {}^{0}_{0}\overline{r}_{P_{Ob_{in}}} \end{Bmatrix} \qquad (3)$$

It may be noted that ${}^{R_1}_{R_1}\overline{r}_{P_{Ob_{in}}}$ is the initial undeformed position of the distal end of fiber $\boldsymbol{P}_{rs}$ - $\boldsymbol{P}_{Ob}$ of the soft material. This is the position before contact takes place at the fiber end. Since the point $\boldsymbol{P}_{rs}$ remains bonded to the link, ${}^{R_1}_{R_1}\overline{r}_{P_{rs_{in}}} = {}^{R_1}_{R_1}\overline{r}_{P_{rs}}$. Two fibers $\boldsymbol{P}$ and $\boldsymbol{Q}$ are considered at the right side of the object, and two fibers $\boldsymbol{U}$ and $\boldsymbol{V}$ are considered at the left side. This is intentional. At least two fibers are required to be considered at each interface. The forces at two points on the surface at the interface have the combined effect of resultant force and moment which is a characteristic feature of the soft contact. This feature becomes more prominent when the effect of all fibers of the soft material is cumulated. The consideration of only two fibers is just representative and has been used here to demonstrate a simplified model.

3.2 Model for the two-joint actuated prosthesis

Consider the two-joint actuated prosthesis shown in Figure 5. In this case, the strings are passed through tubes. The strings have been shown in the figure but not the tubes. The ends of strings are fixed on the second links, while tube ends are fixed on the first links. The connection of strings is clear from the figure. Thus the length of string within the tube remains the same, even though the tube may be moved while using the hand. This



ensures that the string remains taut even when the joint axes move. Frames have been fixed on respective links as shown.

Figure 5. Two-joint actuated string based prosthesis

The Bond graph model for this system is shown in Figure 6.

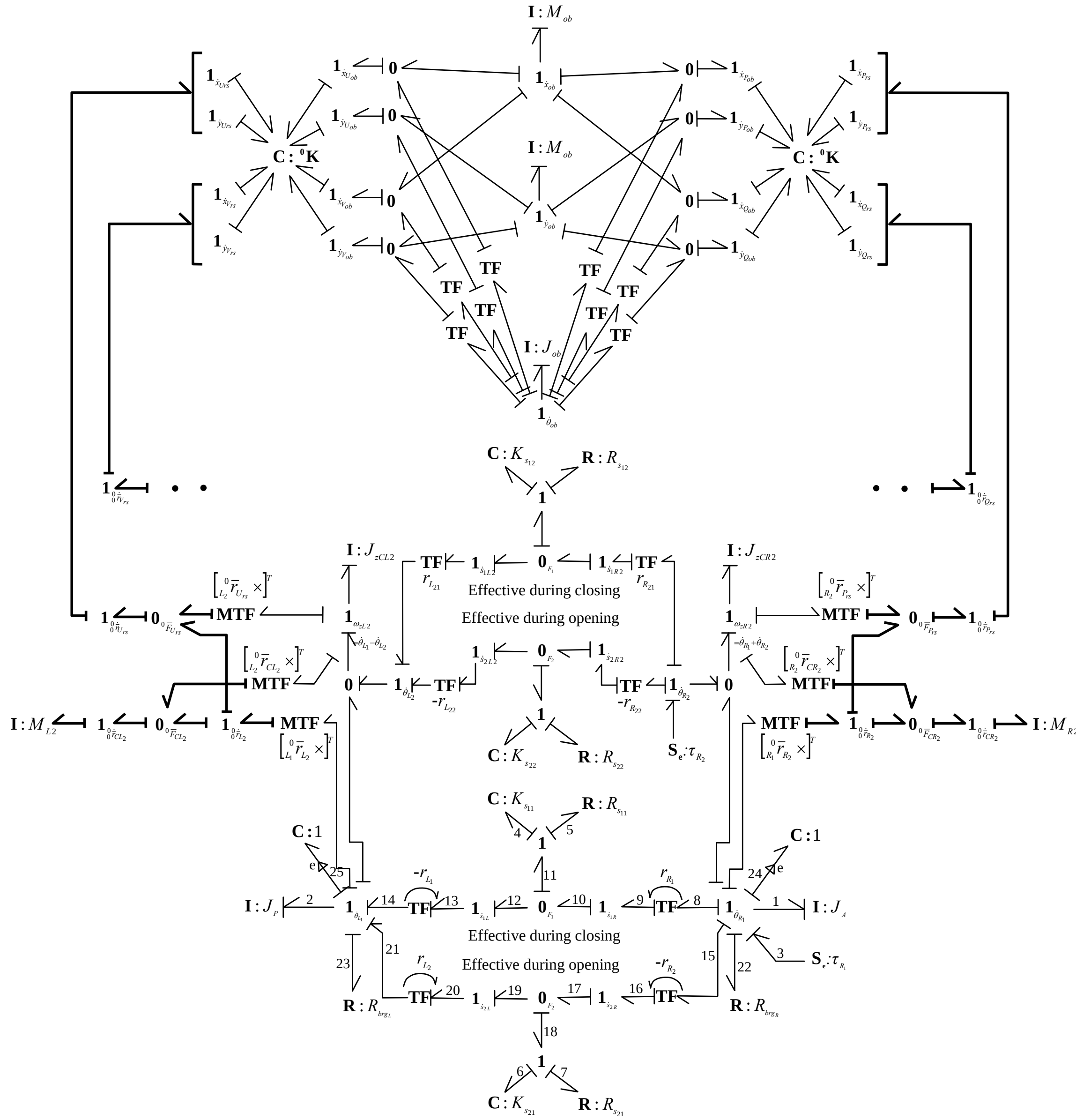


Figure 6. Bond graph for the two-joint actuated string based prosthesis

The portion of the Bond graph corresponding to object dynamics remains the same as before. The previous discussion regarding modeling of the soft material between the rigid object and finger links also holds in this case. The Bond graph of Figure 6 consists of both scalar and vector (multibondgraph) representations [2]. This has been done to avoid cluttering of the figure. A multibond has been shown using a bold line as compared to the usual scalar bond. In the planar case shown, each multibond consists of two scalar bonds.

Mechanics of the string for joint 1 remains the same as before. The mechanics for joint 2 has been added here. Note the change in signs of moduli of the TFs used to model the portion for strings of the second joints. This is on account of the choice of frames. The relative angular velocity component $\dot{\theta}_{R2}$ for the second joint of the right finger is shown by $1_{\dot{\theta}_{R_2}}$. The torque on this second joint due to movement of the active finger is applied on it and is responsible for the actuation of the second joint of the passive finger.

The modulus of each modulated transformer (MTF) has been written on the Bond graph itself. Since it is a planar system, each of the MTF moduli is a 2 x 1 matrix. For example, the vector product term $\left[{}^{0}_{R_1}\overline{r}_{R_2}\times\right]^T$ occurring in one of the MTFs is given as

$$\left[{}^{0}_{R_1}\overline{r}_{R_2}\times\right]^T = \begin{bmatrix} -{}^{0}_{R_1}y_{R_2} \\ {}^{0}_{R_1}x_{R_2} \end{bmatrix} \quad \text{,where} \tag{4}$$

$$ {}^{0}_{R_1}\overline{r}_{R_2} = \begin{Bmatrix} {}^{0}_{R_1}x_{R_2} \\ {}^{0}_{R_1}y_{R_2} \end{Bmatrix}. $$

One can observe the differential causality assigned to the multibond connected to element $\mathbf{I}: M_{R2}$. This is typical in case of rigid body dynamics. One can use stiffness and damping elements to eliminate the differential causality, however, this has not been done here. The elements with differential causality are unable to contribute state variables to the system, and are dependent. For example, the motion of the center of mass of the second right link depends on the variables $\dot{\theta}_{R1}$ and $\dot{\theta}_{R2}$ which are independent.

In the Bond graph, dynamics for the points Q_{rs} and V_{rs}, on the rigid skeletal link, are similar to P_{rs} and U_{rs} respectively. These have not been shown separately to avoid congestion in the figure. The system equations can be systematically obtained from the Bond graph. Moreover the dynamic model thus obtained offers insight into the physical phenomenon of the system.

4 Conclusions

The Bond graph modeling technique has been applied to obtain models of dynamics for prosthetic systems. One and two-joint actuated string based prosthesis have been considered. Modeling of the soft material at the interface, while manipulating a rigid object, has been presented. These models are useful for simulation, design and control of prosthetic systems.

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