A NEW TOOL TO MODEL PHYSICAL SYSTEM: APPLICATION TO THE POWERED GAIT ORTHOSIS SYSTEM FOR HEMIPLEGIC PATIENTS

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ABSTRACT

Modeling and simulating physical systems have given a lot of conveniences for researchers. The purpose of this work is to introduce a new physical modeling tool in Matlab/Simulink R2012b: 2nd Generation of SimMechanics in Simscape tool, and apply to build as well as to control a Biomechanical system: a powered gait training system designed for hemiplegic patients. Firstly, a brief introduction about Simscape and 2nd Generation in SimMechanics was shown. After that, in order to show a practical application of this tool, the process of building and converting the model of the powered gait system for hemiplegia patients from 3D software Inventor model to SimMechanics 2nd Generation was described. In addition, the modeled system is also controlled and made comparison the received results between using classical PID control and artificial intelligence Fuzzy Logic Control (FLC) method. The results showed that we could build a good physical model by using this new tool. Besides, the simulated results also characterized that FLC controller has the better performance compared to PID control method in term of response, disturbance rejection.

KEY WORDS

2nd Generation SimMechanics; Simscape; Biomechanical Modelling; lower limb orthosis; hemiplegic patients; Fuzzy Logic Controller.

1 INTRODUCTION

Simulation is a process of designing a model of an actual or theoretical system, operating the model and analyzing the operation output [1]. Simulating enable us to reduce time from designing to manufacturing process, prevent from injuries, damages, and early find errors. L. Changsong in [2] compared compared physical modeling languages with traditional modeling language. Each modeling language uses block diagram to represent systems. Each block has direct or indirect ports. Block diagrams described in traditional modeling language has only unidirectional signal based on port. Therefore, traditional modeling language is called as an assignment-based representation of mathematic model. On the other hand, block diagram of physical modeling language has bidirectional energy-based ports. As a result, in the physical modeling language we have more detailed understanding about physical execution in the modeling systems. An example of physical modeling language is Simscape/SimMechanics in Matlab/Simulink. Some researchers of [3]- [6] showed two ways to establish the SimMechanics models: one way is by converting the models from 3D softwares to XML file. The other way is by building the model directly in the Simscape environment. SimMechanics 1st Generation in Matlab/Simulink uses the first way and 2nd Generation uses the second one. Although the first method is faster the second one, the disadvantages of this method are the models are built in Simulink platform with dimensionless Simulink signals. Besides, it is difficult to pan, zoom or rotate the models during simulation. In the second one (2nd Generation), it takes quite a lot of time and labor to build the 3D models directly in the Simscape Environment. However, after that we will have physical signal models and have better simulation performance, especially underlying understanding about physical performance of the system. In order to take advantages of the both methods, the new version Matlab R2012b supports conversion and simulation for the models from 3D softwares products to the 2nd Generation of Simscape platform.

The gait training system, that is going to be modeled by using 2nd Generation of SimMechanics in our study, is used for hemiplegic patients. The system is employed for post-stroke or Spinal Cord Injury (SCI) patients in the rehabilitation process. The purpose of rehabilitation is to help patients recover or newly generate their neural pathways that control the locomotion process. The idea to develop this system is that: with different human, they have their own trajectory properties of lower extremities. For the hemiplegic patients, who have one affected side and one unaffected side, it is possible to use the information from the unaffected lower limb to control the affected lower
The purpose of this study is to introduce a new physical modeling tool as well as to model and simulate our proposing powered gait rehabilitation system and to suggest better controlling method for the system. In the field of Control Engineering, classical PID control was widely used because of its simplicity. However, the parameter tuning is one of the remained difficulties. Because real control system has many noise and uncertainty. To resolve this point, Fuzzy Logic Control (FLC) is attracted recently. Therefore, we compared the performance of PID control and FLC.

The remainder of this paper is organized as follows. In the Section II, we briefly introduce about Simscape tool as well as converting principle from 3D software into SimMechanics. Section III represents the modeling process of the system in the Simcape environment. In the Section IV, two control theories which are PID and FLC are applied to control the system and made comparison about the received results. Finally, we summarize an overview of the conclusion and future works in Section V.

2 SIMSCAPE AND CONVERTING MODEL FROM 3D SOFTWARE TO SIMMECHANICS

2.1 Simscape

Simscape is a toolbox for physical modeling developed by Mathworks from version R2007a of MATLAB suite [8]. Simscape extends Simulink with tools for modeling systems spanning mechanical, electrical, hydraulic, and other physical domains as physical networks. The first advantage of physical model in Simscape is that physical network approach allows us to describe the physical structure rather than underlying mathematics as in the Simulink environment. The capabilities of textual authoring for components, domains, libraries are the other good points of Simscape. The new domains created by user can be added into the library and reused or shared after that. The traditional programming language (C, FORTRAN, etc.) and signal-based or input-output method in a graphical software tool such as Simulink is useful for control engineers because of its easy understanding. However, these models are difficult to reuse.

2.2 Export CAD to SimMechanics diagram

When exporting an assembly file from 3D CAD software into Simscape environment we will receive 2 kinds of file which are XML import file and STL file. The SimMechanics XML import file mirrors the hierarchical structure of a CAD assembly, which is followed the order of Root Assembly → Assemblies → Parts. The organization of Root Assembly or Assemblies contains InstanceTree and Constraint that organize the information into reference frame and sets of constraint between Assemblies or parts, respectively. The structure of Part is specified by name, physical unit and especially solid parameters such as mass, center of mass and inertia moments. The STL file specifies 3D geometry of the solid surface for each part.

3 MODELING THE GAIT TRAINING ORTHOSIS SYSTEM USED FOR HEMIPLEGIC PATIENTS

3.1 Human model

The research uses the iMan 3D model whose some basic parameters are available in Table 1 which is based on
military handbook anthropometry of U.S military personnel [9]. In this model, we focus on the lower limb one because we will attach the orthosis system on that. A lower limb can be thought as 7DOFs structure: three rotational DOFs at the hip (in coronal plane: ab/adduction), one at knee and three at ankle (in the coronal plane: e/inversion).

The Figs. 2 (a) and 1 (b) describe the 3D Human model in Inventor environment and 2nd generation of SimMechanics, respectively. The 3DoFs of the hip joint, when they are converted into Simscape, are equal to a Spherical constraint, one DoF of knee joint is equivalent to a revolute constraint. Each part in Inventor environment is correspondingly exported to a 2nd Generation part which has adequate information such as mass, center of gravity, moment of inertia, etc. as in Fig. 1 (a).

3.2 The orthosis system model and wearing the system on human body

3.2.1 The orthosis system used for hemiplegic patients

As aforementioned, each lower limb has 7 DOFs. However, three of 7 DOFs in sagittal plane have large value of ranges [10] and play a very important role in the ambulation. Besides, there are basically two mechanisms for sagittal plane postural control: ankle strategy and hip strategy. In the former one, the body moves forward as an inverted pendulum movement around shank. And in the latter strategy, the horizontal shear force is produced through hip’s rotation. Moreover, Hip motion is the most important motion in gait because the reciprocal movements lead forward powerfully. Therefore, we focused on hip motion (it means the second mechanism). In addition, many hemiplegic patients have foot drop and their foot clearance decreases. In order to increase the foot clearance, we activated not only hip joint, but also knee joint. As a result, in the system hip and knee rotation DOFs in the sagittal plane are powered and controlled. The operation principle of the system (Fig. 2 (a)) as follows: The information about the angle of hip and knee joint at the unaffected lower limb (right leg), used as reference signals, is collected by two potentiometers. At the same time, the angular information of hip and knee on the affected side is also received and transmitted to the computer, to make comparison with the reference signals. These error data are imported to PID or Fuzzy logic controller to derive the control signals for the two DC Servo motors to control affected hip and knee after a fixed delay time. The delay time is the time that the affected lower limb has to wait for changing from swing to stance phase and vice verse. This is necessary because we are using the signal from unaffected leg to control affected leg, but when locomotion if the unaffected lower limb is in swing phase then the affected lower limb is in stance and vice verse.

3.2.2 Model of DC Servo motor

A DC motor can be described as a system with 2 parts, an electrical part and a mechanical part, as illustrated in Fig. 3 (a). The electrical part and mechanical part of the system are described by the differential equations as follow:

\[ v(t) = R_i i(t) + L_i \frac{di(t)}{dt} + K_o \omega(t) \]  \hspace{1cm} (1)

\[ J \omega(t) = K_m i(t) - b \omega(t) \]  \hspace{1cm} (2)
Similarly, we convert the model of the human wearing the system from 3D Inventor environment into 2nd generation SimMechanics of Simscape and result as Fig. 2 (b). The most important notice when converting is redundant constraint rejection. For example, the constraint of human’s hip is Revolute with 2 DoFs. When the system uses two DC Servo motors Maxon RE35 (catalogue number 273752) has the power of 90W, its nominal torque is 0.0732 Nm, \(v(t)\) is the momentary driving voltage, \(R_a\) is terminal resistance, \(i(t)\) is the momentary value of the electric current, \(\omega(t)\) is the momentary angular velocity of the shaft, \(L_a\) is the terminal inductance, \(J\) is the rotor inertia, \(K_a\) is Back EMF constant, \(K_m\) is the torque constant and finally \(b\) is the friction constant. The values of the terms are according to the Maxon catalogue for the RE 35 (273752) as follows: \(V = 15 V, R_a = 0.334 \Omega, L_a = 0.085 mH, K_a = 0.0195 [V/(rad/s)]\), \(J = 676 \times 10^{-7} Kg m^2, K_m = 19.4 Nm/A, and b = K_m \times \frac{b_s}{\omega_p} = 6.42 \times 10^{-6} Nms\), Where \(I_0\) is no load current, \(n_0\) is no load speed. Figure 3 (b) shows the physical model of a DC motor in 2nd Generation of SimMechanics.

### 3.2.3 Model of human wearing system in SimMechanics

Similarly, we convert the model of the human wearing the system from 3D Inventor environment into 2nd generation SimMechanics of Simscape and result as Fig.2 (b). The most important notice when converting is redundant constraint rejection. For example, the constraint of human’s hip in the diagram is Spherical joint with 3DoFs and the constraint of orthosis’s hip is Revolute with 2 DoFs. When we assemble them together, if the Spherical constraint point is not on the axis of the Revolute constraint, the system can’t move although there is no error warning. In the Fig. 2 (b) there are two close loops: the first is the blue color loop which is used to control affected hip joint and the other is the red one to control affected knee joint.

In the current physical model, the model of gearbox is replaced by adding inertia moment on the motor shaft and the increase in output torque as well as the decrease in feedback velocity of the motor. The feedback positions here are the current angles of hip or knee joint at the affected lower limb, while the feedback speeds are velocities of ball screws. In the current version of SimMechanics, the ball screw constraint is not yet supported. As a result, in order to model the ball screw, we took advantage of mathematical model of Simulink by direct converting torque to push or pull force on the nut as in following formulas:

\[
F = \frac{2 \times 3.14 \times T \times e_{bs}}{L}
\]

where: \(F\) (N) is the linear force applied on ball nut, \(T\) (N.m) is driven torque generated by DC Servo motor on the screw shaft, \(L\) (mm) is ball screw Lead and \(e_{bs}\) is ball screw efficiency.

### 4 COMPARISON BETWEEN PID AND FUZZY LOGIC CONTROLLER FOR THE SYSTEM

#### 4.1 PID controller

Using PID tuner in Simulink with GUI, we can get good responses. Fig. 2 (b) shows the system with PID controller. The PID parameters to control two motors of affected hip and knee are shown in Table2.

#### 4.2 Fuzzy logic controller

The classical PID controller represents good performance but not adaptive enough [11]. This is clearer in systems when loads are changed, noise system, especially in the nonlinear system. For our system, whenever we change patient or there is some difference in position of body segments when wearing the system on the patient’s body we have to re-tune to find new PID parameter set. Fuzzy Logic [12] is a technology that is based on the expert knowledge about the system. Building membership functions and base rules is the key problem of a FLC. FLC has demonstrated better performance compared to PID control theory in terms of [13]: better noise rejection, more flexible, no need system’s mathematical model, less sensitive to inertia variation and better performance.

In our system, we use FLC to control the position of DC Servo motors. The structure of the system looks like Fig. 2 (b) but the controller: instead of using PID we use FLC as in the Figure 4. The inputs of FLC are position error \((e)\) and change of error \((ce)\). At sampling point \(k\), \((e)\) and \((ce)\) are calculated as:

\[
e_k = y_{rk} - y_k
\]

\[
ce_k = e_k - e_{k-1}
\]

Where \(y_r\) is the desired response and \(y\) is the actual process response. For a given input condition of \(y_k, e_k\) and \(ce_k\) the

<table>
<thead>
<tr>
<th>Joint</th>
<th>(K_p)</th>
<th>(K_i)</th>
<th>(K_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip’s Motor</td>
<td>6.42</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Knee’s Motor</td>
<td>3.23</td>
<td>0</td>
<td>0.2</td>
</tr>
</tbody>
</table>
FLC will calculate the motor voltage input. The fuzzy controller consists of three stages: fuzzification, Inference engine and defuzzification. The fuzzification procedure uses triangular membership function due to its simplicity. The error and change of error for the hip’s Fuzzy logic controller are designed to operate in the ranges of [-50, 50] and [-90, 90], respectively. These values for the knee’s FLC are [-60, 60] and [-280, 280] correspondingly. The output control voltage range is [-15, 15]. Fig. 5 (a), (b), (c) are membership functions for FLC of the affected hip joint motor. The fuzzy linguistic variables are defined as NB: Negative Big, NM: Negative Medium, NS: Negative Small, Z: Zero, PS: Positive Small, PM: Positive Medium and PB: Positive Big. In this work, we use the weighted average method for the defuzzification procedure. The Figure 6 represents the rule viewer for fuzzy inference system.

4.3 Simulation results and discussion

4.3.1 Normal trajectories

Figure 7 represents the simulation results in two control methods: the PID and FLC theories. The cycle time is 2 [Sec]. The parameters used in the controllers are mentioned above. The continuous lines are unaffected hip and knee trajectories, the dot lines are responses of affected hip and knee trajectories in case of using PID controller, and the dash lines are responses of affected hip and knee trajectories when using Fuzzy logic controller. There is not so big difference between the responses in two control methods. However the FLC method gives better responses than the PID method: the affected hip and knee trajectories track better the control signals from unaffected lower limb.

4.3.2 Noise disturbance rejection simulation.

An attempt to compare the noise disturbance rejection capability between two control methods, a White Gaussian Noise, which chosen mode is Signal to noise ratio and the ratio of bit energy to noise power spectral density Eb/No= 10 (dB), was added to the control signals. Both PID and FLC control method were implemented. Figure 8 is the results of noise disturbance rejection of the system in cases of using PID controller (dotted lines) and Fuzzy logic controller (dashed lines). It is clear that, the FLC can resist the noise disturbance better than PID controller.

5 CONCLUSION AND FUTURE WORKS

This paper introduced a newly physical modeling tool in Simscape environment, the 2nd Generation of SimMechan-
ics, and the process of exporting 3D model from Inventor environment to Simscape platform. A complete system which includes human body and a lower limb orthosis system designed for hemiplegic patients were also shown in this paper. To control the system, two methods of PID and FLC were applied and we made a comparisons about control accuracy. As a result, a good physical model. Besides, it also demonstrated the better points of FLC compared to the classical control method of PID. In the future, an autotuning FLC should be developed. After that it is necessary to make experiments on the system and evaluate the results.

REFERENCES


