MODELING AND CONTROL OF MCKIBBEN ARTIFICIAL MUSCLE – APPLICATION OF MODEL PREDICTIVE CONTROL AND GENETIC ALGORITHMS

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ACRONYMS

PID Proportional-Integrative-Derivative

MPC Model Predictive Control

Part I

THESIS

1 INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

The current state of the art in hydraulic actuators consists almost entirely of oil driven valves, pistons and motors. However, this kind of actuator cannot be used in some particular applications, such as power assist systems and rehabilitation: they have significant heaviness and rigidity, because of their mechanical structure and motorization [1]. In this context, it is problematic to share a robot working space with humans around it, and so this kind of actuator cannot be used to actuate, for example, orthotics.

McKibben muscles were invented by Joseph L. McKibben to motorize pneumatic art orthotics. They in general consist of an inner rubber tube enclosed in a braided outer nylon sleeve. These muscles can be used as actuators of rehabilitation systems due to the following advantages:

- Light weight
- High power to weight ratio
- High flexibility
- Low cost
- Low environmental impact

However, there are drawbacks: it is well known that the muscle has poor control performance due to the existence of strong nonlinearities, such as hysteresis and saturation characteristics. Furthermore, the wear of the materials (nylon sleeve and rubber tube) may cause a shorter lifetime with respect to other actuators.

1.2 MODELING OF MCKIBBEN ARTIFICIAL MUSCLE

As already mentioned, the control of McKibben muscles is not easy to achieve. A PID control solution may be developed, but it has flaws: the parameters of the controller will have to be tuned different types of muscles and for various loads. This is generally not an acceptable solution for this kind of application.

Thus, model-based control techniques are better suitable for this job. The plant model needs to be very precise for the control to be effective, and to do so identification techniques are used to get a first linear approximation of the model. Later, a hysteresis component is added to this linear model, to keep track of the nonlinearities added by the hysteretic behaviour of the muscle. Adding a hysteresis component to a linear model makes it more complex, so the choice of an appropriate hysteresis modeling technique is crucial to achieve good control performance.

This allows to get a model having good fit with respect to the real one and apply a model-based control approach, namely the **Model Predictive Control** (MPC). Further details about the developed controller are in Chapter 5, and the theory behind MPC can be found in Appendix A.

1.3 AIM OF THE STUDY

The aim of this dissertation is to get precise control of the displacement for a tap water-driven McKibben artificial muscle. To do so, a list of steps will be followed:

1. *Derivation of a Simple Linear Model*

   Using linear identification techniques, it is possible to map the input pressure to the output displacement, and get a precise yet simple linear model of the muscle. While in pneumatic artificial muscles it is required to take into account the temperature dynamics and the compressibility of air, using water as the muscle allows to disregard them. This grants a simpler model of the muscle.

2. *Introduction of a Hysteresis Component*

   The linear identification method grants a very simple yet linear model that does not take nonlinearities into account. The biggest source of nonlinearity for the McKibben muscle is hysteresis. A hysteresis component is added to the linear model, so that it will better follow the actual behaviour of the muscle. This step is essential to get good control performance.

3. *Controller Design*

   The application of Model Predictive Control and Adaptive Control techniques are proposed, using the muscle model obtained from linear system identification and modified with the introduction of the hysteresis component. these results are confronted with PI and PID control.

4. *Adaptive Parameter Estimation*

   Model's parameters change according to the load of the muscle and its working conditions. To retain good control performance, an adaptive estimation is needed to update the controller, and achieve perpetual stable results. To do so, a {Genetic Algorithm}/{LS} approach is proposed.

2 COMPOSITION OF THE THESIS

3 TAP WATER-DRIVEN MCKIBBEN ARTIFICIAL MUSCLE

4 MODELLING OF MCKIBBEN ARTIFICIAL MUSCLES

In this Chapter, the muscle models used as nominal models for model-based control are derived.

4.1 INTRODUCTION

McKibben muscles are actuators used mainly for medical purposes in rehabilitation and welfare. The reason is their high flexibility, light weight, low cost, human and environmental friendliness and ease of use. As mentioned in Chapter 1, the control of this kind of actuators is often problematic, due to their inherent high nonlinearity.

Many muscle models have been proposed, both static and dynamic. One of the most known static models is derived by Chou [2], which is based on the equilibrium between the input pressure and the release of energy. Although the main interest is to obtain the dynamic model to use in control, the static one is also reviewed and evaluated because they are used with feed-forward control applied to rehabilitation devices using the McKibben muscle.

Dynamic muscle models can be categorized in analysis oriented and control oriented. Analysis oriented models provide very high accuracy, but they are also very complex. For this reason they are not much suitable for control purposes.

Control oriented models provide lower accuracy than analysis oriented ones, but their lower complexity allows them to be used more efficiently for control.

Since tap water driven muscles are simpler than pneumatic ones, the idea is to use linear system identification and obtain a simple model of the muscle's dynamics. Being this only a linear model, it does not take into account the presence of strong nonlinearities, such as the friction between the braids and the hysteretic behaviour of the muscle. However, the introduction of a hysteresis model can lead to achieving higher precision with the model derived from linear system identification.

Through history, several hysteresis models have been developed. Notable examples are the Maxwell-slip model [3], the Jiles-Atheron model [4] and the Preisach model [5]. Common interest points of these models are friction of the braided sleeve, and the hysteresis caused by it, which both add nonlinearities to the model.

These hysteresis models are precise, yet complex in structure. To overcome this problem, the Bouc-Wen [6] [7] hysteretic model is combined with the identified muscle model. Including the hysteretic model raises the number of parameters that have to be identified for the system, but this is easily achieved, at first, by trial and error. Later, an adaptive algorithm is developed to get the best parameters for the muscle, and thus the updated model can be use as a nominal model for model-based control techniques.

The accuracy of the proposed model is compared to experimental results by analysing the pressure–displacement characteristics and the hysteresis characteristics. Moreover, the effects of changing the load of the muscle are studied, because they may have a great impact upon control performances.

4.2 STATIC MODEL

4.3 INTRODUCTION

The relationship between the axial contraction force and the pressure difference amid supply and atmospheric pressure has been reported in different papers [8] [9].

The association is based on the equilibrium between the input work in the McKibben muscle (i. e. when the fluid is supplied to the inner rubber tube) and the output work (i. e. when the actuator shortens or elongates because of the volumetric change associated with the pressure difference).

Figure 1 shows the geometric structure, which follows the geometric relationships in Equation **??**.

$$L = b\cos(\gamma), \quad D = \frac{b\sin(\gamma)}{n\pi} \tag{1}$$

4.3.1 *Static Model of the Muscle*

The input work W_{in} is applied to the muscle when the fluid (liquid or air) pushes the internal surface of the rubber tube. This can be expressed as the product of the supply pressure and the change in volume.

$$dW_{in} = (P - P_0)\,dV = P'dV \tag{2}$$

Where P is the supply pressure, P_0 is the atmospheric pressure, P' is the pressure difference and dV is the volumetric change.

Equation 3 shows the volume of the muscle, with the assumption that it has cylindrical shape.

$$V = \frac{1}{4}\pi L D^2 \tag{3}$$

5 CONTROLLER DESIGN

Part II

APPENDICES

APP A

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