IRREVERSIBILITY MODELING APPLIED TO THE CONTROL OF COMPLEX ROBOTIC DRIVE CHAINS

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Abstract: The phenomena of static and dry friction may lead to difficult problems during low speed motion (e.g. stick slip phenomenon). However, they can be used to obtain irreversible mechanical transmissions. The latter tend to be very hard to model theoretically. In this paper, we propose a pragmatic approach to model irreversibility in robotic drive chains. The proposed methodology consists of using a state machine to describe the functional state of the transmission. After that, for each state we define the efficiency coefficient of the drive chain. This technique gives conclusive results during experimental validation and allows reproducing a reliable robot simulator. This simulator is set up for the purpose of position control of a medical positioning robot.

1 INTRODUCTION

Modern control theories in robotics are more and more turned towards model-based controllers such as computed torque controllers, adaptive controllers or feedforward dynamics compensators. Therefore, dynamic modeling has become an inevitable step during controllers design. Besides, accurate dynamic modeling is a key point during simulations and the mechanism design process.

In the literature, the problem of robot dynamic modeling is treated in two steps. The first one concerns the mechanical behavior of the robot external structure considered often as a rigid structure. Many researchers have treated this problem and different techniques have been introduced to solve this issue. The two best-known methods in this matter are the Newton-Euler formulation and the Lagrange formulation (Khalil, 1999). The second step concerns the drive chain modeling which includes motors, gears and power loss modeling. Despite the advances made in the field of mechanical modeling, some issues are still without a convenient solution. We can mention, for instance, the phenomenon of irreversibility that characterizes certain types of mechanical transmissions such as worm gears (Henriot, 1991). This characteristic is often required for security reasons like locking the joint in case of motor failure or unexpected current cut-off. The purpose of this paper is to present a new modeling approach based on a state machine in order to simulate irreversible transmissions.

This paper is organized as follows. In section 2, we give a brief overview of the LCA vascular robot, which is used as an application for this study. Section 3 presents details about the modeling approach used for the robot structure and drive chain. Section 4 presents the irreversibility modeling issue and the proposed solution. Section 5 illustrates the experimental validation results. Finally, section 7 presents some concluding remarks.

2 LCA ROBOT PRESENTATION

The LCA vascular robot (figure 1) is used for medical X-ray imaging. It is a four-degrees-of-freedom open-chain robot composed of the following links: the L-arm (rotational joint), the Pivot (rotational joint), the C-arc (it has a translation movement in a circular trajectory template. Hence, it

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can be considered as a rotational joint around the virtual axis crossing the C-arc center) and the Lift (prismatic joint)

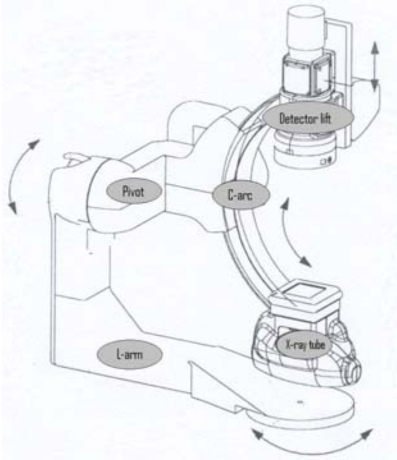
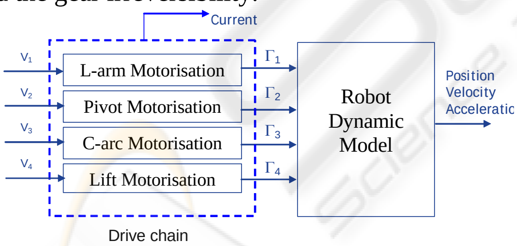


Figure 1: LCA robot.

3 MODELING APPROACH

The modeling of the LCA robot requires a clear distinction between the dynamic model of the mechanical structure and the drive chain model (figure 2). In fact, the dynamic model describes merely the relation between the applied torques and the ideal mechanical reaction of the gantry given by the joints acceleration.

The drive chain model takes into account the hard nonlinearities of the system such as the joint friction and the gear irreversibility.



V_i are the motors command voltage. Γ_i are the axes driving torques.

Figure 2: The robot model structure.

3.1 Dynamic Modeling

Two main methods can be used to calculate the dynamic model of the robot mechanical structure. We can mention the Newton-Euler formulation and the Lagrange formulation (Khalil, 1999).

Most authors use the Lagrange formulation that gives the mathematical expression of the model as:

$$\Gamma = A(q)\ddot{q} + C(q,\dot{q})\dot{q} + Q(q) \qquad (1)$$

Where $q, \dot{q}, \ddot{q}$ are respectively the vectors of joints position, velocity, and acceleration.

$A(q)$: the 4x4 robot inertia matrix.

$C(q,\dot{q})\cdot\dot{q}$: the 4x1 Coriolis and centrifugal torque/ forces vector.

$Q(q)$: the 4x1 gravitational torques/ forces vector.

Γ : the 4x1 input torques/ forces vector.

To simulate the robot movement, we should use the inverse of the dynamic model as follow:

$$\ddot{q} = f(\Gamma, \dot{q}, q)$$

This model can be obtained directly using the recursive Newton-Euler equations, or it can be inferred from equation (1):

$$\ddot{q} = A(q)^{-1}(\Gamma - C(q,\dot{q})\dot{q} - Q(q)) \qquad (2)$$

The "A" matrix is inverted symbolically; this will result in a heavy mathematical expression, costly in term of computation time. Alternatively, this inverse can be calculated after numerical calculation of $A(q)$ which leads to faster simulations.

3.2 Drive Chain Modeling

The next step consists of modeling the drive chain, which includes the electrical motor (DC motor for this application), the mechanical transmission (gears) and the elements of power dissipation (friction) (figure 3).

We will describe briefly the first and the second elements and emphasize the third element, which is the purpose of this paper.

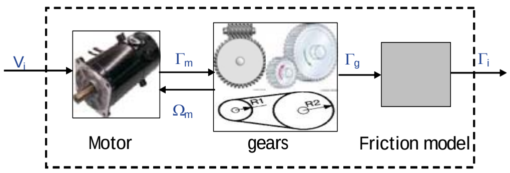


Figure 3: Drive chain model.

Actually, the phenomenon of irreversibility, obtained using specific transmissions and particular geometric dimensioning, is a complex problem and leads instinctively to non linear models. It can be treated using several approaches. In a microscopic point of view, the contacts among driving and driven elements are modeled as well as the applied forces. However, this rigorous approach leads to very complex analytical models, with serious difficulties in the implementation and simulations phases, particularly in the case of closed loop structures including controllers (Henriot, 1991). Besides, the identification of this type of models is very complicated due to the significant number of parameters. In a macroscopic point of view, the power transfer between the motor and the load is modeled with an efficiency coefficient taking into account the power transfer direction (load driving/driven) (Abba, 1999), (Abba, 2003). However, a proportional coefficient is insufficient to represent the irreversibility behavior. In our approach, we suggest the use of a state machine to define the current functional state of the transmission in order to reproduce the irreversibility.

3.2.1 DC Motor Modeling

The DC motor is a well-known electromechanical device. Its model has two inputs, the armature voltage and the shaft velocity. The output is the mechanical torque applied on the shaft. The DC motor behavior is modeled using two equations (Pinard, 2004) the electrical equation of the armature current (3) and the mechanical equation of the motor torque (4):

$$V - E = R \cdot I + L \cdot \frac{dI}{dt} \quad (3)$$

where V is the motor voltage. I is the armature current. $E = K_{emf} \cdot \dot{q}_m$ is the electromotive force. $\dot{q}_m$ is the motor velocity; and the motor parameters are: K_{emf} (the back electromotive constant), R (the motor resistance) and L (the motor inductance).

$$\Gamma_m = K_t \cdot I \quad (4)$$

where Γ_m is the motor torque and K_t is the motor torque constant ($K_t = K_{emf}$)

3.2.2 Gears Modeling

In this paper, we consider rigid gears' models. In this case, the model's mathematical expression depends only on the gear ratio *N*. Therefore, the output torque is obtained using the following relation: $\Gamma_g = N \cdot \Gamma_m$ and the speed of the motor shaft is obtained using: $\dot{q}_m = N \cdot \dot{q}$.

The gear's ratio is given by simple mathematical expressions (Henriot, 1991) or via the gears datasheet.

3.2.3 The Power Dissipation in Drive Chain

This section is the most essential in drive chain modeling. In fact, good power dissipation modeling helps to reproduce complex gear behaviors such as irreversibility. The power dissipation will be illustrated through the friction phenomenon.

In robotics, friction is often modeled as a function of joint velocity. It is based on static, dry and viscous friction (Khalil, 1999), (Abba, 2003). These models produce accurate simulation results with simple drive chain structures. However, in the presence of more complex mechanisms such as worm gears these models lack reliability.

To illustrate this phenomenon, we can compare the theoretical motor torque required to drive the LCA pivot axis in the case of a reversible transmission and the real measured motor torque. Figure 4 and 5 show the applied torques on the pivot axis during a 7°/sec and -7°/sec constant velocity movement.

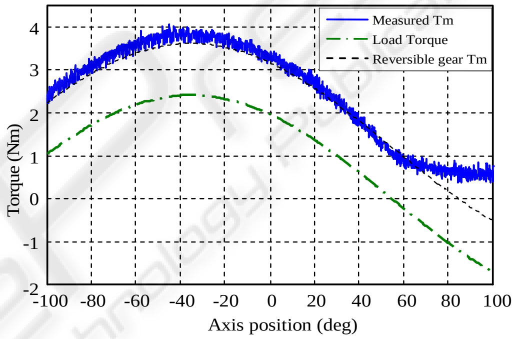


Figure 4: Motor and load torque variation during constant velocity rotation (7 °/s).

During this movement, the robot dynamic is represented by the following dynamic equation:

$$\Gamma_m = \Gamma_l + \Gamma_f \quad (5)$$

where Γ_l is the load torque and Γ_f is the friction torque. Consequently, we expect that the motor torque will have the same behavior as the load torque because the friction torque is constant. However, these results reveal an important difference between the measured motor torque and the expected motor torque with a drive chain using only velocity friction model.

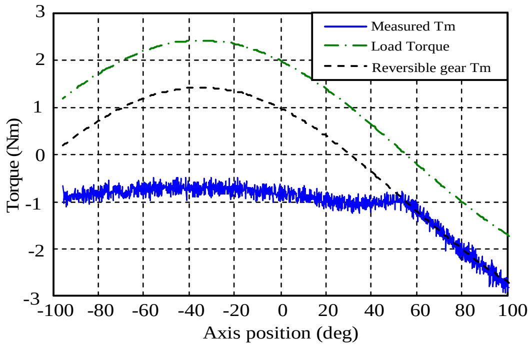


Figure 5: Motor and load torque variation during constant velocity rotation (-7 °/s).

We can see that the irreversibility seriously influences the motor torque. Actually, the irreversibility compensates the gravity torque when the load torque becomes driving. Therefore, it is essential to expand the friction model to take into consideration more variables such as motor torque and load torque in order to reproduce irreversibility in a simulation environment. Thus, the friction model Γ_f applied on motor shaft will have the following structure:

$$\Gamma_f = \Gamma_{fs}(\Gamma_m, \dot{q}_m) + \Gamma_{fv}(\dot{q}_m) + \Gamma_{fT}(\Gamma_m, \Gamma_l, \dot{q}_m) \quad (6)$$

where :

$\Gamma_{fs}(\Gamma_m, \dot{q}_m)$: 4x1 vector of the static friction model

$\Gamma_{fv}(\dot{q}_m)$: 4x1 vector of the velocity friction model

$\Gamma_{fT}(\Gamma_m, \Gamma_l, \dot{q}_m)$: 4x1 vector of the torque friction model.

Γ_{fs} and Γ_{fv} are the classical friction terms used usually in drive chain modeling (Dupont, 1990), (Armstrong, 1998). While, Γ_{fT} presents the term that takes account of the irreversibility behavior.

$$\Gamma_{fTi}(\Gamma_{mi}, \Gamma_{li}, \dot{q}_{mi}) = \mu_{mi}(\Gamma_{mi}, \Gamma_{li}, \dot{q}_{mi}) \cdot \Gamma_{mi} + \mu_{li}(\Gamma_{mi}, \Gamma_{li}, \dot{q}_{mi}) \cdot \Gamma_{li} \quad (7)$$

where $\mu_{mi}(\Gamma_{mi}, \Gamma_{li}, \dot{q}_{mi})$ and $\mu_{li}(\Gamma_{mi}, \Gamma_{li}, \dot{q}_{mi})$ are the motor and load friction dynamic coefficients.

Let's consider now the complete robot dynamic model:

$$\Gamma_m = J_m \cdot \ddot{q}_m + N^{-1} A(q) \ddot{q} + \Gamma_l + \Gamma_f \quad (8)$$

where $\Gamma_l = N^{-1}(C(q,\dot{q})\dot{q} + Q(q))$ and J_m is the 4x4 motors and gears inertia matrix. By replacing (6) in (8) we obtain:

$$\Gamma_m = (J_m + N^{-2} A(q)) \cdot \ddot{q}_m + \Gamma_l + \Gamma_{fs}(\Gamma_m, \dot{q}_m) + \Gamma_{fv}(\dot{q}_m) + \mu_m \cdot \Gamma_m + \mu_l \cdot \Gamma_l \quad (9)$$

where μ_m and μ_l are respectively 4x4 diagonal matrixes:

$$\mu_m = \operatorname{diag}\{[\mu_{mi}(\Gamma_{mi}, \Gamma_{li}, \dot{q}_{mi})]\,;\, i = 1, \ldots, 4\}$$
$$\mu_l = \operatorname{diag}\{[\mu_{li}(\Gamma_{mi}, \Gamma_{li}, \dot{q}_{mi})]\,;\, i = 1, \ldots, 4\}$$

By regrouping the terms of equation 11 we obtain:

$$\eta_m \cdot \Gamma_m = (J_m + N^{-2} A(q)) \cdot \ddot{q}_m + \eta_l \cdot \Gamma_l + \Gamma_{fs}(\Gamma_m, \dot{q}_m) + \Gamma_{fv}(\dot{q}_m) \quad (10)$$

where $\eta_m = (I_{4\times4} - \mu_m)$ and $\eta_l = (I_{4\times4} + \mu_l)$.

The new terms η_m and η_l, which depend on Γ_m, Γ_l and $\dot{q}_m$, introduce the efficiency concept in the robot dynamic model. The next section will focus on the proposed approach used to calculate the drive chain efficiency coefficients.

4 EFFICIENCY COEFFICIENTS ESTIMATION

One of the complex issues in drive chain modeling is the estimation of the transmission efficiency coefficient. One technique consists of theoretically calculating the efficiency of each element of the drive chain using the efficiency definition (Henriot, 1991):

$$\eta = \frac{|\text{Received Power}|}{\text{Emitted Power}} = \frac{|P_{out}|}{P_{in}} \quad (11)$$

The calculation of this coefficient requires the determination of the driving element whether it is the motor or the load. We talk then about the motor torque efficiency (η_m) or the load torque efficiency (η_l). Therefore, the received power "P_{in}" could be either from the motor or the load.

Actually, this method can be applied with simple gear mechanisms such as spur gears, whereas for complex gears, such as worm gears, the calculation of the efficiency coefficient using analytical formulas tends to be hard and inaccurate due to the lack of information concerning friction modeling as well as the complexity of the contact surface between gears' components (Henriot, 1991). The alternative that we propose is to experimentally identify the efficiency coefficient according to a functional state of the drive chain, for instance, when the load is driving the movement or when the motor is driving the movement. This leads us to create a state machine with the following inputs and outputs:

Table 1: State machine inputs and outputs.

Inputs	Outputs
Γ_m : motor torque (Tm) Γ_l : load torque (Tl) $\dot{q}_m$: motor velocity	η_m : motor efficiency η_l : load efficiency

Now, we will present the states and the criteria of states transitions that we have used for LCA robot drive chain modeling. The state machine includes two levels: the upper level that describes the motion (figure 6) and the lower level that describes the switch between motor driving and load driving states (figures 7, 8), and associates an efficiency coefficient for each state. In this level, the transition condition is the sign of the velocity.

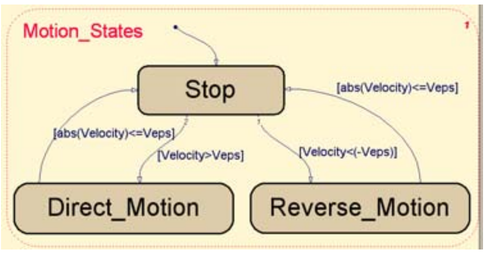


Figure 6: Motion state machine.

In the upper level, the transition condition is the sign of the velocity. In fact, for simulation convergence issue the drive chain is considered stopped when $|\dot{q}_m| < V_{eps}$, where V_{eps} is the stop velocity threshold.

In the lower level, a sub-state has been combined to each motion state:

- **The stop states (figure 7)**

During the stop phase, the drive chain is irreversible (the load torque cannot drive the movement). Motion is observed when the motor torque becomes superior to the load torque.

In the lower level, the state transition is based on the motor and load torque values. As for V_{eps} (figure 6), Tm_{eps} represents the motor torque threshold, it is used for simulation convergence issue ($Tm_{eps} = 10^{-5}$ Nm).

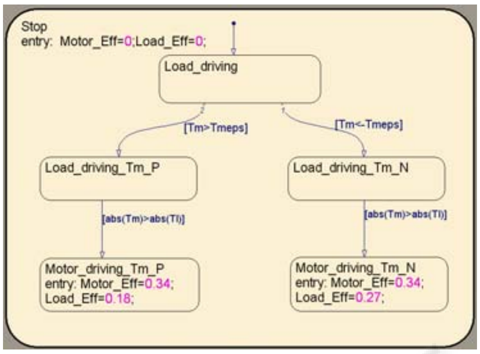


Figure 7: Stop state machine.

- **The direct motion states**

For the direct motion state (if V>0), we have four main states (figure 8), the states transitions are given by the following conditions: $\Gamma_m > 0$ and $\Gamma_l < 0$: the motor is driving; $\Gamma_m > 0$ and $\Gamma_l > 0$: we distinguish two states whether $\Gamma_l > \Gamma_m$ or not; and $\Gamma_m < 0$: the motor is braking (load driving)

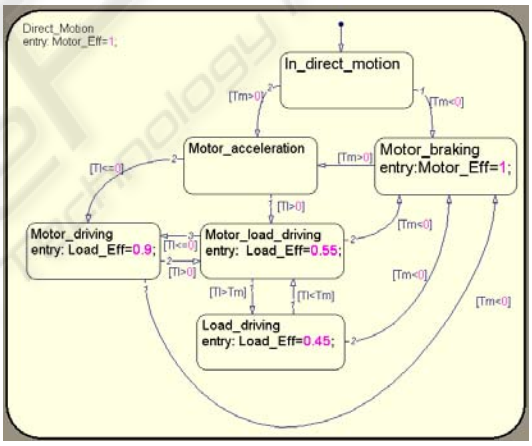


Figure 8: direct motion state machine.

- **The reverse motion states**

The reverse motion (V<0) state machine has the same structure as the direct motion one. We need to replace Γ_m and Γ_l by $-\Gamma_m$ and $-\Gamma_l$. The table 1 summaries the drive chain efficiency coefficients for each state: (Motor driving / Motor and load driving / Load driving).

Table 2: Drive chain efficiency coefficients.

States	Direct motion η_l	Reverse motion η_l
1-$\Gamma_m \cdot \Gamma_l < 0$	0.9	0.9
2-$\Gamma_m \cdot \Gamma_l > 0$ & $\lvert\Gamma_m\rvert < \lvert\Gamma_l\rvert$	0.55	0.16
3-$\Gamma_m \cdot \Gamma_l > 0$ & $\lvert\Gamma_m\rvert > \lvert\Gamma_l\rvert$	0.45	0.06

5 EXPERIMENTAL VALIDATION

The validation of the drive chain model has been done on the pivot axis. The efficiency coefficients have been identified using experimental measures.

We compare the open loop response of the pivot joint and the simulation results to a voltage input for both direct and reverse motion. Figure 9 shows the applied voltage on the motor pivot axis for direct motion. Figure 10 shows the experimental results (dashed curve) of current, velocity and position and those obtained in simulation (solid curve). We notice in that the simulation response represents the same behavior as the real mechanism. In this figure we distinguish four main phases: the starting phase 24s to 25s, the motor driving phase 25s to 37.8s, the load driving phase 37.8s to 4.2s and the braking phase 4.2s to 4.3s.

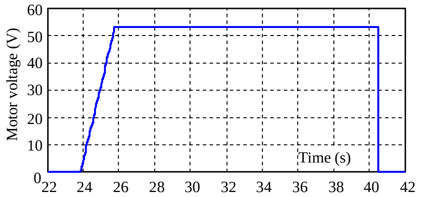


Figure 9: Open loop motor command voltage.

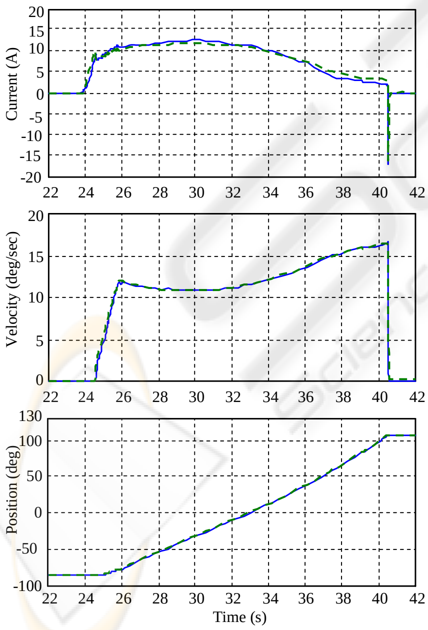


Figure 10: Direct motion outputs.

By comparing the obtained results, we notice that the differences are low for direct motion as well as for reverse motion. Therefore, these results prove that the used model is able to represent accurately the irreversibility property of the pivot drive chain.

6 CONCLUSIONS

In this paper, we presented a methodology in order to model the irreversibility characteristic in electromechanical drive chains. The proposed approach uses a macroscopic modeling of the gears, which are usually the origin of irreversibility in a drive chains. It consists of creating a state machine representing different functional states of the gears and attributing an efficiency coefficient to each specific state.

The validation of the proposed modeling was carried out on the Pivot axis of the LCA robot. The methodology has been tested in particular when the position trajectory leads to some transitions “motor driving to load driving” and the obtained results confirm the correctness of the used model.

The perspectives of this work concern two research orientations. The first one is the definition and the study of an automatic procedure to identify the efficiency coefficient for each state. The second one is the investigation of the trajectory planning and the control of robots with irreversible transmissions when considering state machines for gear’s modeling.

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