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Non Linear Position and Closed Loop Stiffness Control for a Pneumatic Actuated Haptic Interface: the BirthSIM

Nicolas Herzig, Richard Moreau, Tanneguy Redarce, Frédéric Abry and Xavier Brun

Abstract—This paper presents the BirthSIM model, a haptic interface of a childbirth simulator. The aim of this haptic interface is to improve haptic rendering and increase the biofidelity of the movements and forces which occur during the fetal descent. Thus the model of this 2 degrees of freedom pneumatic actuated interface is presented in this article, in order to synthesize a control law based on the backstepping method. The control law obtained allows targeted trajectories of positions and pneumatic stiffness to be tracked but also allows the equivalent stiffness of the end effector in Cartesian coordinates to be adapted in real time. The difference between pneumatic stiffness and closed loop stiffness is explained. Finally, some simulation results are presented to validate the control law behavior.

I. INTRODUCTION

Fortunately, most childbirths do not require practitioner intervention. But in some cases the obstetricians and the midwives have to be prepared to face different issues. On the other hand, C-sections are more and more used, to the detriment of other tools like forceps or vacuums. The lack of use of these tools leads to a loss of some skills and technical gestures, whereas they are more appropriate than C-sections in some cases. The BirthSIM and some other childbirth simulators have been developed in order to answer this issue and give to the practitioner a way to learn and practice some specific gestures used during delivery.

Different approaches have been discussed to design a childbirth simulator. Some simulators only use virtual reality [1] lack of a haptic interface decreases realism and does not allow forces during the gesture to be evaluated. Therefore, most childbirth simulators include a haptic interface. Different designs of haptic interfaces have been developed, for instance Sielhorst *et al.* [2] have decided to use a 6 degrees of freedom (DOF) industrial robot. The benefit of this kind of robot is that they are accurate and easy to use, but they are expensive and the effort ranges of the actuators are often over-sized to be used as haptic interface of a medical simulator. On the other hand, Abate *et al.* [3] have chosen an exoskeleton for haptic interface. This kind of haptic interface is a good way to reproduce hand and finger haptic sensations, but it is less suitable to simulate tool-assisted delivery.

Kheddar *et al.* have concluded in [4] that some industrial haptic interfaces appear to be limited and that developing a dedicated interface seems to be more suitable to simulate childbirth delivery. The BirthSIM has been developed in this

way. At first the BirthSIM has been designed especially to practice forceps-assisted delivery, but with the different improvements, the current version of this simulator is able to simulate different scenarios in which forceps are needed or not [5][6]. The latest version of the BirthSIM is 4 DOF robot actuated by two pneumatic cylinders and two motors. The pneumatic actuators have been chosen not only because the range of effort and displacement which are suitable to reproduce childbirth but also for their natural compliance which is suitable to simulate soft tissues behavior. The design, direct geometric model (DGM) and inverse geometric model (IGM) of the latest version of the BirthSIM have been presented in [7].

This paper will present the BirthSIM model which will be used to design a control law. In the first part, the global hardware architecture will be explained. The second part will describe the different steps to model the haptic interface and the hypothesis which have been chosen. The developed control law, which is presented in this paper, is a stiffness control based on the nonlinear theory which allows a targeted trajectory to be reached but also allows the stiffness of the actuator to be tuned in real time. These controlled pneumatic actuators can be used as variable stiffness actuators. It enables a better haptic feedback and best simulates the delivery behavior. The last parts will deal with the control law synthesis and discuss the future works.

II. HARDWARE DESIGN OF THE BIRTHSIM

As introduced in the previous section, the BirthSIM is an haptic interface which simulate childbirth delivery. To be more precise, this robot is design to reproduce the fetal head movements during its descent inside the maternal pelvis. According to the obstetricians and the midwives, four DOF of the fetal head seem to be more important. This four DOF are the two translations of the center of the fetal head inside the sagittal plane of the maternal pelvis, the flexion of the fetal head and finally the internal rotation. That is the reason why the BirthSIM have been designed to reproduce those DOF but in this paper, the two last rotations will not be taken into account. Indeed, the stiffness control synthesis is more suitable for the pneumatic cylinder and does not concern the two rotations. The two neglected electric motors will actuate the end effector orientation and these rotations does not affect the dynamic behavior presented in section III. The position control of these two motors is based on a classical linear approach and have been widely addressed in literature. So, in order to simplify the study, the two motor and rotation have been removed. Fig. 1 shows the equivalent

N. Herzig, R. Moreau, T. Redarce, F. Abry and X. Brun are with the Laboratoire Ampère, UMR CNRS 5005, Université de Lyon, INSA-Lyon, F-69621 Villeurbanne Cedex, France (e-mail: firstname.lastname@insa-lyon.fr).

kinematic scheme of the BirthSIM, without the two motors. The two prismatic joints model the two pneumatic cylinders. The cylinder which consists of links 3 and 4 will be denoted cylinder 1. Cylinder 2 consists of links 1 and 2.

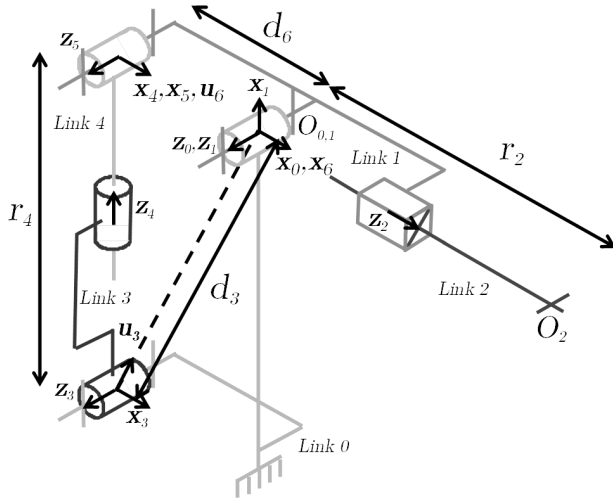


Fig. 1: Kinematic scheme of the BirthSIM's simplified architecture

Fig. 2 provides the global hardware architecture. The two actuators are two *Festo* pneumatic cylinders. The main characteristics are given in table I.

TABLE I: Main characteristics of the cylinder

Reference	DSNU-25-400-PPV-A-Q	DSNU-25-200-PPV-A
Notation	cylinder 2	cylinder 1
Position	horizontal	vertical
Stroke	400 mm	200 mm
Piston diameter	25 mm	25 mm
Theoretical force at 6 bar, advancing	295 N	295 N
Theoretical force at 6 bar, retracting	247 N	247 N
Rod geometry	square	cylinder

Each chamber of each cylinder is supplied by a independent *Festo MPYE-5-M5-010-B* proportional servovalve. A 5/3-way proportional servovalve¹ to supply only one chamber is not necessary but in the final version only one servovalve per cylinder will be used so a 5/3-way proportional servovalve will then be necessary. Four pressure sensors are used to measure the pressure of each chamber. The end effector position and rotation are tracked by a 6 DOF *Ascension trakSTAR* magnetic tracker.

The control board chosen for the BirthSIM is a *dSPACE* board which allows sensors signals to be acquired and servovalves control to be generated. The code is generated with *Matlab/Simulink* which is suitable for control prototyping.

¹5/3-way proportional servovalve means that the valve has 5 inputs/outputs and 3 positions, proportional means that the spool position is proportional to the voltage applied to the valve

III. MODEL

In this section, the goal is to present the appropriate model of the BirthSIM to deduce a control law. The model is obtained by taking into account the mechanical behavior of the robot but also the thermodynamic behavior of the pneumatic part.

A. Geometric model

The DGM and IGM of the BirthSIM have been presented in [7]. In this paper, only the two prismatic active joints defined by the parameters r_4 and r_2 (cf. Fig. 1) are considered. To obtain the geometric model, the Khalil and Kleinfinger method have been used [8]. This method is known to be suitable for closed-loop robots modeling. In the procedure, each closed-loop is cut at a passive joint and a cut joint variable is introduced using a modified Denavit-Hartenberg parameterization. Finally, equating the two ending frames generates the geometric constraint equations. Table II gives the geometric parameters of the simplified architecture of the BirthSIM:

TABLE II: Geometric parameters of the BirthSIM

j	$a(j)$	σ	μ	b	d	r	γ	α	θ
1	0	0	0	0	0	0	0	0	θ_1
2	1	1	1	0	0	r_2	0	$\frac{\pi}{2}$	0
3	0	0	0	0	$-d_3$	0	γ_3	0	θ_3
4	3	1	1	0	0	r_4	0	$-\frac{\pi}{2}$	0
5	4	0	0	0	0	0	0	$-\frac{\pi}{2}$	θ_5
6	1	2	0	0	d_6	0	$-\frac{\pi}{2}$	0	0

For the next section, the passive joint variable θ_1 and the cut joint variable θ_5 have to only be expressed with the active joint variables r_4 and r_2 . To do so the geometric constraint equations have to be solved. These equations model the behavior of the closed loop made up of the links 0,1,3, and 4. After solving these equations, the solutions obtained are

$$\begin{aligned} \theta_1 &= \gamma_3 - \arcsin\left(\frac{r_4^2 - d_3^2 - d_6^2}{2d_3d_6}\right), \\ \theta_5 &= \arcsin\left(\frac{r_4^2 + d_6^2 - d_3^2}{2d_3r_4}\right). \end{aligned} \quad (1)$$

To simplify the further equation, new variables are defined for the piston positions of cylinder 1 and 2 respectively, $y_1 \in [-\frac{l_1}{2}; \frac{l_1}{2}]$ and $y_2 \in [-\frac{l_2}{2}; \frac{l_2}{2}]$, with l_1 and l_2 the strokes of cylinders. y_1 and y_2 are respectively the piston position of cylinder 1 and 2. So there exist $(k_1, k_2) \in \mathbb{R}^2$ such that

$$r_4 = y_1 + k_1, \quad r_2 = y_2 + k_2. \quad (2)$$

B. Dynamic Model

This section will deal with the dynamic behavior of the robot. The objective is to obtain a model suitable for control synthesis. In order to simplify the control design and reduce the time spent on parameters identification, some assumptions have been made. The assumptions are as follow

- All the links are supposed to be rigid bodies
- All the revolute joints are supposed to be perfect

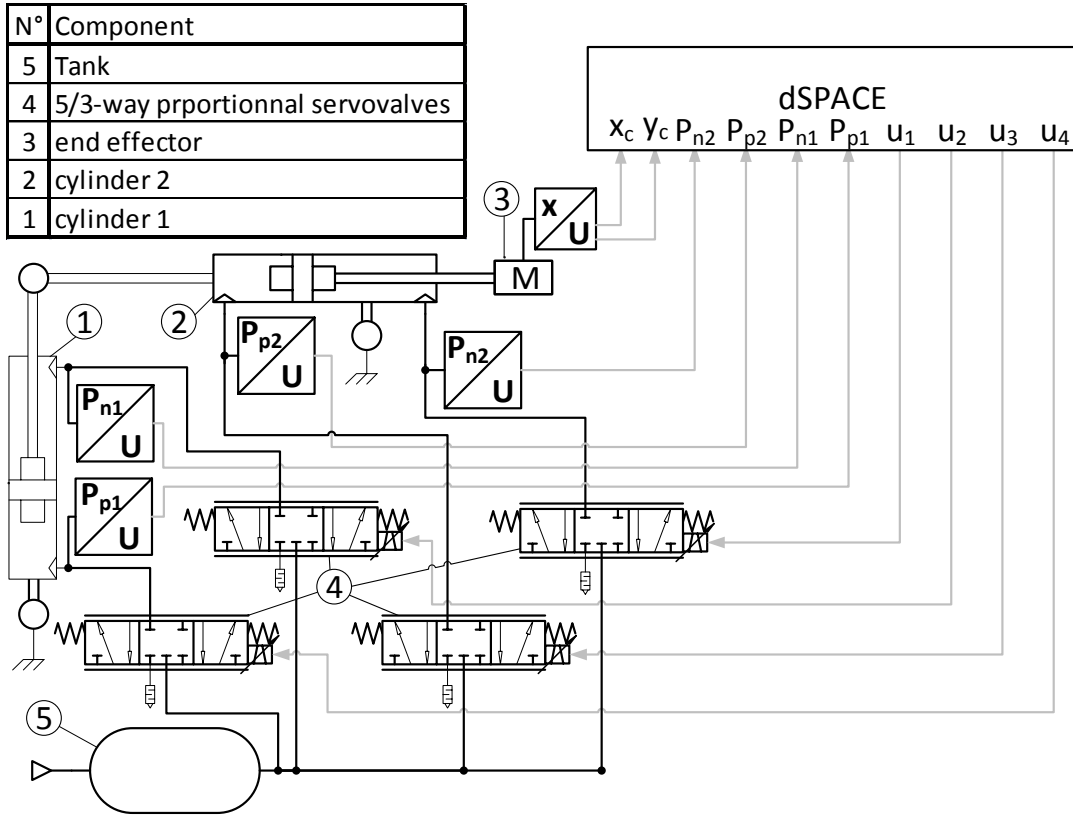


Fig. 2: Hardware architecture of the BirthSIM

- End effector is modeled as a point mass at O_2 (cf. Fig. 1)
- All other masses and moments of inertia are neglected compared to that of the end effector

In this case, the forces taken into account are the weight of the end effector W , the pneumatic forces applied by the two cylinders F_{pneu1} and F_{pneu2} , the forces applied by the external pressure F_{pext1} and F_{pext2} , the friction forces F_{f1} and F_{f2} applied on cylinder 1 and 2 respectively.

The pneumatic forces of the cylinder can be deduced from the chambers' pressure measures whereas the external pressure forces only depend on the atmospheric pressure, which is assumed to be constant

$$\begin{aligned} F_{pneu i} &= P_{pi} S_{pi} - P_{ni} S_{ni}, \\ F_{pext i} &= P_{atm} (S_{pi} - S_{ni}). \end{aligned} \quad (3)$$

P_{pi} and P_{ni} are respectively the pressures in P and N chamber of the i cylinder, P_{atm} the atmospheric pressure, S_{pi} and S_{ni} are the effective piston areas in chamber P and S of the i cylinder.

The friction model for the two prismatic joints is composed of Coulomb friction with viscous friction. Indeed, the friction force for cylinder i is written

$$F_{fi} = F_{ci} \text{sign}(v_i) + F_{vi} v_i, \quad (4)$$

with $v_i = dy_i/dt$ the velocity of cylinder i piston, F_{ci} and F_{vi} the Coulomb and viscous friction parameters of cylinder

- i . Then with the Newton-Euler method, the time derivative of v_1 and v_2 can be deduced

$$\left\{ \begin{aligned} \frac{dv_2}{dt} &= \frac{F_{pneu2} - F_{pext2} - F_{f2}}{m} + g \cos(\theta_1) \\ &+ \frac{4(y_2 + k_2)(y_1 + k_1)^2 v_1^2}{4d_3^2 d_6^2 - ((y_1 + k_1)^2 - d_3^2 - d_6^2)^2} \\ \frac{dv_1}{dt} &= \frac{\sqrt{4d_3^2 d_6^2 - ((y_1 + k_1)^2 - d_3^2 - d_6^2)^2}}{2(y_2 + k_2)(y_1 + k_1)} \\ &\left(g \sin(\theta_1) - \frac{d_6 \cos(\theta_7)}{m(y_2 + k_2)} (F_{f1} + F_{pext1} - F_{pneu1}) \right) \\ &- \frac{2(y_1 + k_1)((y_1 + k_1)^2 - d_3^2 - d_6^2) v_1^2}{4d_3^2 d_6^2 - ((y_1 + k_1)^2 - d_3^2 - d_6^2)^2} \\ &- \frac{2v_1 v_2}{y_2 + k_2} - \frac{v_1^2}{y_1 + k_1} \end{aligned} \right. , \quad (5)$$

where g is the Earth gravity coefficient.

C. Thermodynamic model

A common model used in literature to model the thermodynamic behavior inside the pneumatic cylinder chamber is based on polytropic law. The hypothesis that the temperature variation in the chambers are negligible [9] is assumed to design a non linear control law. In that case the model

first cylinder stays low. That is the reason why the centrifugal acceleration is considered to be bounded. On the other hand, the weight projection on \mathbf{z}_2 (cf. Fig. 1) is also bounded in the robot workspace. In the subsection III-A, it has been shown that θ_1 is bounded around $\pi/2$ so the weight projection is bounded around zero. So in the next section the model used to synthesize the control is the one given in (13) but without \dot{f}_2 .

B. Controller synthesis

As it has been explained, the backstepping method has been used to obtain the control law. Using two servovalves for each cylinder allows two independent trajectories for each cylinder to be tracked, that is four for BirthSIM robot. Two DOF will be used to track the desired position of the pistons y_{d1} and y_{d2} respectively for cylinder 1 and 2. To define the trajectory the derivatives of these positions are needed, the desired velocities v_{d1} , v_{d2} , the desired accelerations a_{d1} , a_{d2} and the desired jerks j_{d1} and j_{d2} . The two left DOF will be used to track the desired pneumatic stiffness' trajectories, K_{pneud1} and K_{pneud2} , defined by their derivative dK_{pneud1}/dt and dK_{pneud2}/dt .

The method used to obtain the control law is the same as that presented by Abry *et al.* in [12][15] for the four first states and then reiterated for the following four. This method introduces some gains which will allow the closed loop stiffness of the actuators to be tuned. In electro pneumatic field, two different stiffnesses can be defined. The first one is the pneumatic stiffness defined in (9). This stiffness is a state of the system, it shows the actuator tendency counteract an external force. But the displacement due to this external force will depend of the piston position. The second one is the closed loop stiffness, this stiffness is a parameter which depends on the control law gains. By tuning this parameter, the behavior of the pneumatic actuator against an external disturbance (force) can be chosen. Indeed for a force $F_{disturb}$ applied on the actuator, the displacement of the piston will be

$$\Delta y = \frac{F_{disturb}}{K_{cl}}. \quad (15)$$

The Abry *et al.* method enable the control of the closed loop stiffness of each actuator, but for a robotic haptic interface, it is more useful to control the end effector equivalent stiffness. So it is necessary to compute the closed loop stiffness of both cylinder K_{cl1} and K_{cl2} from a desired end effector stiffness in cartesian space K_{clx} and K_{cly} . To do that, the kinematic model is needed. The kinematic model is obtained by derivation of the geometric model

$$\begin{bmatrix} dx_c \\ dy_c \end{bmatrix} = J(y_1, y_2) \begin{bmatrix} dy_1 \\ dy_2 \end{bmatrix}, \quad (16)$$

where dx_c and dy_c are respectively the cartesian end-effector coordinate x_c and y_c differentials and J is the Jacobian matrix of the robot.

Due to the force-velocity duality, with quasi-static assumption, the relation between external forces applied on end-effector F_{usx} and F_{usy} and equivalent forces on actuators

F_{us1} and F_{us2} is given by

$$\begin{bmatrix} F_{us1} \\ F_{us2} \end{bmatrix} = J^T \begin{bmatrix} F_{usx} \\ F_{usy} \end{bmatrix}. \quad (17)$$

It can be deduced that the equivalent closed loop stiffnesses are obtained by computing the next equations

$$\begin{aligned} K_{cl1} &= \begin{bmatrix} 1 \\ 0 \end{bmatrix}^T J^T \begin{bmatrix} K_{clx} & 0 \\ 0 & K_{cly} \end{bmatrix} J \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \\ K_{cl2} &= \begin{bmatrix} 0 \\ 1 \end{bmatrix}^T J^T \begin{bmatrix} K_{clx} & 0 \\ 0 & K_{cly} \end{bmatrix} J \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \end{aligned} \quad (18)$$

The global architecture of the controller is shown by Fig. 3. The servovalve static characterizations are obtained experimentally. These characterizations give for each servovalve the voltage which has to be applied to obtain a desired mass flow for given pressure inside the chamber.

V. SIMULATION

In this section, the controller obtained by backstepping is tested in simulation. The objective is to validate the assumption taken in IV-A and to show that it is possible to follow a desired trajectory and to control the closed loop stiffness.

It is noteworthy that the model used for the simulation is more complex than the model used to synthesize the control law. Indeed, if the model presented in this paper are suitable and enough simple to synthesize the control law, they are not necessary the most accurate to model the system. More over in order to verify that the assumptions taken to simplify the control model does not impact the desired behavior of the system too much, using a more complex model for the simulation is suitable. Thus, the simulation model takes account of the centrifugal acceleration and the weight projection presented in (14). The dynamic model also includes the forces applied by the user on the haptic interface F_{usx} and F_{usy} . The thermodynamic model used in the simulation is not a polytropic model with a constant temperature, but a model with heat exchange between the two chambers and between the chambers and the external environment. Finally, the servovalves are modeled as first order systems with an estimated time constant.

Fig. 4 shows simulation results. In this simulation the targeted trajectory is a circle in Cartesian coordinates. The user disturbance in cartesian coordinate and the setpoints of closed loop stiffness are shown on Fig. 4a. The same sequence is repeated twice, once with a closed loop stiffness set at 2000 N/m on both cartesian axes x_c and y_c and the second time with a stiffness doubled. It is not obvious to define a targeted trajectory of pneumatic stiffness. For instance, this state could be used to optimize air consumption, but for the BirthSIM, this kind of objective is not a priority. In this paper, the main idea is to illustrate the difference between the closed loop stiffness and the pneumatic stiffness. For this reason, it has been chosen to reduce the pneumatic stiffness whereas the closed loop stiffness is increased in order to show that they are independent. Fig. 4b presents the targeted and real trajectories of pneumatic stiffness for each cylinder.

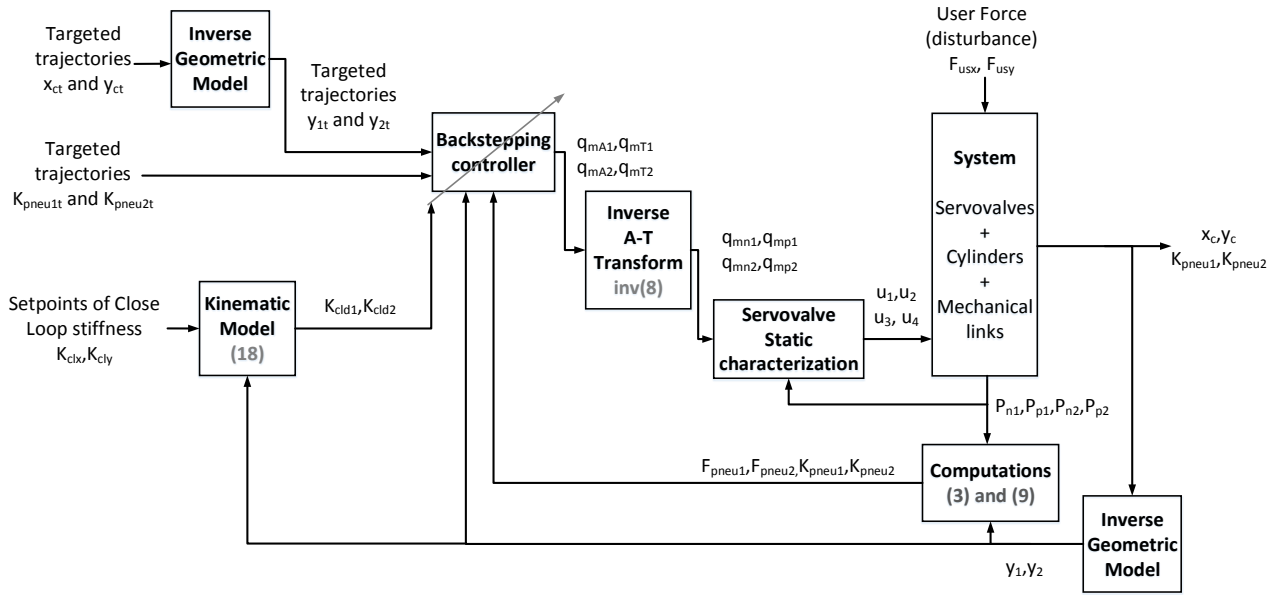


Fig. 3: Architecture of the controller

Fig. 4c shows the targeted trajectory and the real trajectory in cartesian space. And finally, Fig. 4d shows the targeted trajectory and the real trajectory of the cartesian coordinates. In this figure the x_{ck} and y_{ck} are obtained by adding the estimated displacement due to disturbance to the targeted trajectories.

$$\begin{aligned} x_{ck} &= x_{ct} + \frac{F_{usx}}{K_{clx}}, \\ y_{ck} &= y_{ct} + \frac{F_{usy}}{K_{cly}}. \end{aligned} \quad (19)$$

In Fig. 4c and 4d, the expected behavior is obtained. This simulation shows that it is possible to reduce the pneumatic stiffness of each actuator and also increase the closed loop stiffness. That is why it is important to distinguish them. Others scenarios have been played on this simulation. It has been noticed that, for lower disturbances, assuming that the weight effect on cylinder 2 can be neglected, too much error is induced. That is why, another control law is about to be developed with a weight compensation for cylinder 2.

VI. CONCLUSIONS AND FUTURE WORKS

The control model of a two DOF pneumatic robot has been presented. The difference between the closed loop stiffness and the pneumatic stiffness has been illustrated by a simulation. Finally, it has been shown that for this kind of robot it is possible to develop a control law which not only allows targeted trajectories of position and pneumatic stiffness to be tracked but also enable real time tuning of the closed loop stiffness.

In the near future, this control law will be tested experimentally on the BirthSIM robot. Some improvements will be added to the current control law. The first point will be to add a weight compensation for cylinder 2. The second point is to reduce the number of servovalves. Indeed, the servovalves are expensive so it could be a way to reduce the

price of a pneumatic robot. By removing a servovalve per cylinder, the control of pneumatic stiffness is lost but, the closed loop stiffness tuning can be preserved.

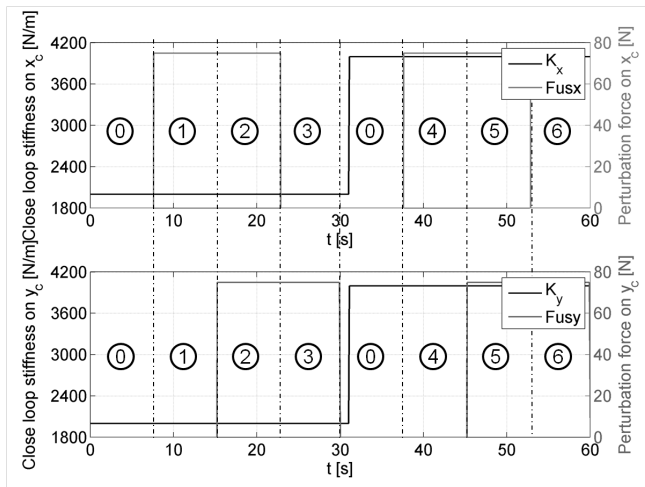
In order to use the BirthSIM as an haptic interface which reproduce childbirth delivery, some data of fetal head movement are needed to define the targeted trajectories of positions and the setpoints of closed-loop stiffness. Obtaining this data by *in vivo* measurement is difficult because of ethical issues. So to overcome this issue some partners of the SAGA project (French acronym for simulator to learn delivery gestures) work on a biomechanical model of childbirth delivery which will compute fetal head trajectories and will also allow the stiffness to be estimated [16][17][18]. Of course, all this data will be validated by expert practitioners.

ACKNOWLEDGMENT

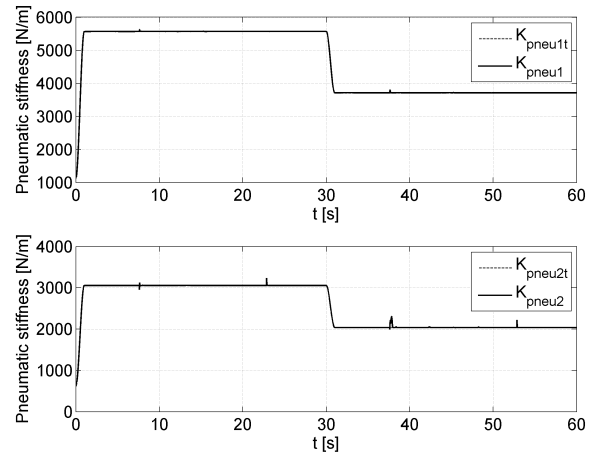
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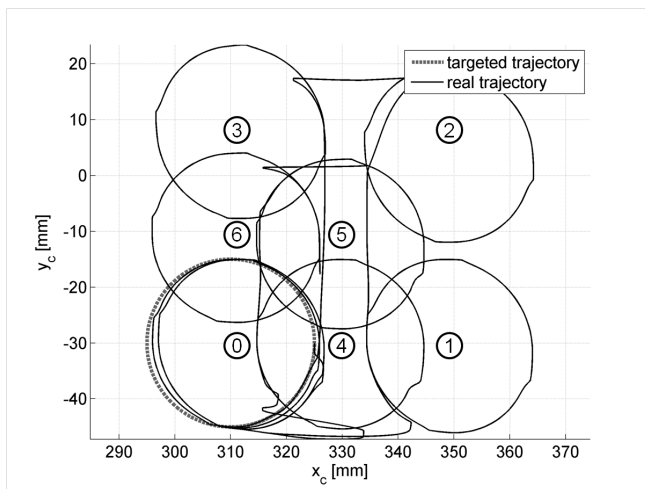
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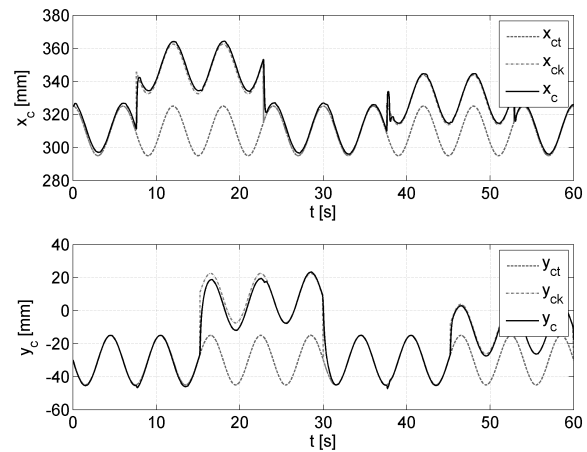
(a) User disturbance and closed loop stiffness setpoints



(b) Pneumatic stiffness



(c) Cartesian position



(d) Cartesian coordinates

Fig. 4: Simulation results

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