On the Modelling and Controller Design for the Outpouring Phase of the Pouring Process

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Abstract: - The present work contributes towards modeling and control of the outpouring phase of a pouring process, where the liquid container is carried by a robotic manipulator. The dynamics of the liquid motion are approximated by the well-known pendulum-type model, where the length and the mass of the pendulum vary with time due to liquid outpouring. The dynamics of the liquid transfer structure, including the carrying manipulator, the container and the liquid, are approximated by the dynamics of a robotic structure that incorporates virtual prismatic joints and corresponding weightless links to represent variations of the liquid level and corresponding variations of the pendulum length within the tank. The performance of a two stage control design scheme on the control of liquid outpouring and the suppression of liquid sloshing during the outpouring phase of the pouring process is studied for the derived model using simulation results. The designed scheme combines a partial inverse dynamics controller with a PID controller, tuned with the use of a "metaheuristic" search algorithm. Both controllers have been designed for a nominal model, ignoring the loss of liquid's mass due to outpouring.

Key-Words: - Robotic applications, Robot Control, Nonlinear Control, Pouring Process, Sloshing Control

1 Introduction

Control of liquid pouring is a highly demanding task, that is met in several industrial applications, as for example metal casting and steel industries. The control design goals that appear in such industrial applications concern suppression of liquid sloshing during liquid transfer, as well as control of liquid outpouring with simultaneous sloshing suppression during the pouring process (see f.e. [1]–[19] and the references therein). The pouring process may be divided in three phases: the forward tilting phase, the outpouring phase and the backward tilting phase. During the forward tilting phase, the tank tilts until it reaches the maximum critical angle at which no liquid outpouring takes place provided that the liquid's surface remains horizontal. During the outpouring phase, additional tilting takes place to cause liquid outpouring. When the desired amount of liquid has outpoured the tank, the tank tilts backward to the equilibrium position. This is the third and last phase of the pouring process, namely the backward tilting phase.

Control of liquid pouring is complicated due to several factors, as the nonlinearity of the pouring process behavior, difficulties on deriving a model that describes efficiently the process dynamics, the lack of direct actuation of the liquid's motion and the lack of measurements of the liquid's displacement. During the outpouring phase, parameters of the liquid, as the liquid's mass and level within the tank vary with time, fact that complicates significantly modeling and control design.

A widely used approach to simplify modeling of the liquid's dynamics is to approximate the liquid's motion by a pendulum-type model [1]-[3], [5]-[12], [15], [16], [18], [19]. More specifically, the liquid's vibrations are approximated by the oscillations of a pendulum, whose mass and length are determined by the mass of the liquid and the natural frequency of liquid's oscillations, respectively [2], [4]. Obviously, variations of the liquid's mass and level within the tank during the outpouring phase results to corresponding variations of the pendulum's mass and length.

Regarding control of the pouring process, several control design approaches, as for example input shaping control, application of time varying filter gain and hybrid shape approach, have been proposed to control liquid vibrations for several cases of liquid transfer and pouring (see f.e. [1]–[19] and the references therein).

In [8] and [9] a two stage control scheme has been applied, that combines a partial inverse dynamics controller with a heuristically tuned PID controller for the case of a liquid container carried by a manipulator. The proposed controllers do not require measurements of the liquid's motion within the tank. However lack of measurements of the liquid's motion does not allow to fully linearize the system using an inverse dynamics controller. Thus, the proposed partial inverse dynamics controller is designed to achieve I/O decoupling and feedback linearization in the ideal case where the liquid's surface does not oscillate. Then, an additional PID controller is applied to suppress sloshing, thus keeping the liquid's level oscillations sufficiently small. The PID controller parameters are tuned using a metaheuristic search algorithm, introduced in [20], that solves numerically using simulation results an appropriately formulated optimization under constraints problem. For more details on metaheuristic algorithm see for example [21]-[23] and the references therein.

In [8] the two stage control scheme has been successfully applied for sloshing suppression during liquid transfer, while in [9] a similar scheme has been appropriately adjusted to prevent undesirable liquid outpouring and suppress sloshing during the forward and backward tilting phases of the pouring process. In the case of liquid transfer [8], the tank's rotations are used exclusively to suppress sloshing. However, during the pouring process [9], the tank has to rotate appropriately so as to cause or prevent liquid outpouring. In this case sloshing suppression has to be achieved simultaneously with command following for the tank's rotation.

As already mentioned, modeling and control of the outpouring phase is more demanding due to loss of liquid's mass. More specifically, time variations of the pendulum's mass and equivalent length have to be considered in the pendulum–type model that approximates the liquid's motion within the tank, as well as time variation of the liquid's level within the tank.

A simplified modeling of the outpouring phase the case of the liquid container carried by a manipulator has been proposed in [18], that constitutes an introductory version of the present work. This simplified model has been derived by simply incorporating time variation to specific parameters of the time-invariant dynamic equations that model the tilting phases of the pouring process, during which the liquid's mass and level remain constant. To provide a better approximation of the plant's dynamics, we propose in the present work another simplified modeling approach. Here, the dynamics of the whole liquid transfer structure, including the carrying manipulator, the container and the liquid, are approximated during the outpouring phase by the dynamics of a robotic structure that incorporates virtual prismatic joints and corresponding weightless links to represent variations of the liquid level and corresponding variations of the pendulum length within the tank. Then, the performance of the two stage control design scheme for control of liquid outpouring and suppression of sloshing during the outpouring phase is studied for the simplified model derived using the aforementioned consideration. The proposed controllers have been designed for the dynamic model that describes the tilting phases, thus ignoring the time variation of the pendulum's parameters due to loss of liquid's mass and considering the mass and the equivalent length of the pendulum, as well as the liquid's level to remain constant.

Section 2 presents the modeling equations of the automatic pouring system during the tilting phases and introduces the proposed modeling approach for the outpouring phase. Moreover Section 2 presents the design goals that have to be satisfied by the control scheme. Section 3 presents the proposed time-invariant control design approach. Finally, Section 4 presents simulation results from the application of the proposed controller to the automatic pouring system.

2 Problem Formulation

2.1 Time-Varying Pendulum-Type Model

As already mentioned, the liquid's motion within a container may be approximated by a pendulum-type sloshing model [1]-[3], [5]-[12], [15], [16], [18], [19]. The mass $m_p(t)$ of the pendulum is equal to the mass of the liquid within the container at each instant of time, which can be computed by the relation:

$$m_p(t) = \frac{m_{p,0}}{h_{s,0}} h_s(t) \tag{1}$$

where $h_s(t)$ denotes the liquid level within the container at each instant of time, while $m_{p,0}$ and $h_{s,0}$

denote the mass and the level, respectively, of the liquid within the tank before initiation of the outpouring phase.

The equivalent length $l_p(t)$ of the pendulum is determined based on the natural frequency given by the perfect fluid theory [2], [4]. Assuming the dimension of the sloshing mode to be equal to one, the natural frequency $f_s(t)$ is related to the liquid level $h_s(t)$ according to the relation [2], [4]

$$f_s(t)=\frac{1}{2\pi}\sqrt{\frac{g\pi}{R}\tanh\left(\frac{\pi h_s(t)}{R}\right)} \qquad (2)$$

where R the distance between the walls of the liquid's container. Then the length $l_p(t)$ is given by

$$l_p(t)=\frac{g}{4\pi^2 f_s^2(t)} \qquad (3)$$

Let $\eta(t)=q_l(t)-q_t(t)$ denote the angle between the liquid's surface and the bottom of the tank, where $q_l(t)$ the angle between the liquid's free surface and the horizontal axis and $q_t(t)$ the angle of the tank's rotation with respect to the perpendicular axis. Let also $\eta_c(t)$ denote at each instant of time, the critical value of the angle $\eta(t)$ at which liquid outpouring initiates, that is the value of $\eta(t)$ at which the liquid's surface reaches the edge of the container. This critical value depends on the liquid's level $h_s(t)$ according to the relation

$$\eta_c(t)=\tan^{-1}\left(\frac{2\left(h_t-h_s(t)\right)}{R}\right) \qquad (4)$$

where h_t the height of the tank. Relation (4) implies that at each instant of time at which the angle $\eta(t)$ is such that the liquid's surface reaches the edge of the container ($\eta(t)=\eta_c(t)$), the liquid's level $h_s(t)$ can be determined by the relation

$$h_s(t)=h_t-\frac{R}{2}\tan\left(q_l(t)-q_t(t)\right) \qquad (5)$$

Equation (5) may be used to express the loss of liquid's mass during the outpouring phase. More specifically, consider that the outpouring phase initiates at $t=0$, which implies that

$$\eta(0)=\eta_c(0)=\eta_{c,0}=\tan^{-1}\left(\frac{2\left(h_t-h_{s,0}\right)}{R}\right).$$

Then, using (5) it follows that the rate of variation of the liquid's level $h_s(t)$ can be determined by

$$\dot{h}_s(t)=\begin{cases}-\dfrac{R}{2}\dfrac{\dot{\eta}(t)}{\cos^2\left(\eta(t)\right)}, & \eta(t)=\eta_c(t) \text{ and } \dot{\eta}(t)\geq 0\\ 0, & \eta(t)<\eta_c(t) \text{ or } \dot{\eta}(t)<0\end{cases} \qquad (6)$$

Determination of the equivalent length $l_p(t)$ depending on liquid's level $h_s(t)$ is valid for relatively small values of the angle $\eta(t)$. When $\eta(t)$ is large the distribution of the liquid's mass within the tank changes, and the natural frequency should be computed from (2) using smaller values of $h_s(t)$ than that corresponding to the equilibrium state. However, it is significant to note that the function at the right hand side of (2) saturates for sufficiently large values of $h_s(t)$. Thus, the natural frequency $f_s(t)$ and consequently the length $l_p(t)$ remain practically invariant provided that $h_s(t)$ remains sufficiently large.

2.2 Modeling Equations of the Tilting Phases

Consider an automatic pouring system, consisting by an articulated robotic manipulator carrying the liquid container (Figure 1). Liquid pouring is accomplished by appropriately tilting the container, through an actuatable revolute joint that connects the tank with the robot's end effector. The tank is firmly grasped by the robotic manipulator's end effector. Liquid sloshing is neglected in directions that do not lie on the structure's plane of motion. The liquid container is represented by a single link, whose mass m_t and inertia I_t are equal to the corresponding parameters of the tank (Figure 2). This link is modeled as an additional third link of the robotic manipulator, considering the size, the mass and the moment of inertia of the robot's end-effector to be neglectable. Liquid sloshing is modeled by the pendulum-type sloshing model introduced in Subsection 2.1 (Figure 2). The pendulum rotates freely around a point of the third joint located at a distance l_t from the tank's center of rotation CR, which denotes the distance of CR from the liquid's free surface. When no liquid outpouring takes place, the dynamics of the liquid transfer structure may be approximated by the Euler-Lagrange dynamic equations of the robotic system presented in Figure 2, namely [8], [9]:

$$D\big(q(t)\big)\ddot{q}(t)+C\big(q(t),\dot{q}(t)\big)\dot{q}(t)+G\big(q(t)\big)=u(t) \quad (7)$$

where $q=\begin{bmatrix}q_1 & q_2 & q_t & q_l\end{bmatrix}^{\mathrm{T}}$, with q_1 and q_2 being the generalized variables of the robotic manipulator, $u=\begin{bmatrix}u_1 & u_2 & u_3 & 0\end{bmatrix}^{\mathrm{T}}$, where u_1, u_2 and u_3 denote the control torques that actuate the first manipulator joint, the second manipulator joint and the joint actuating the tank's motion, respectively. Model (7) incorporates also a torque on the pendulum due to viscosity. Finally, $D(q), C(q,\dot{q})$ and $G(q)$ are matrices of appropriate dimensions, incorporating as constant parameters the liquid's mass m_p, the pendulum's length l_p and the distance l_t.

2.2 Modeling Equations of the Outpouring Phase

During the outpouring phase these parameters vary with the liquid's level $h_s(t)$, and consequently with time, according to relations (1), (2), (3), (6) and

$$l_t(t)=l_{t,0}+h_s(t)-h_{s,0} \quad (8)$$

where $l_{t,0}$ the initial value of l_t, before initiation of outpouring. Thus, the dynamic equations (7) are no longer valid. In order to derive a simplified model of the liquid transfer structure during the outpouring phase we make use of the following considerations: We consider two virtual prismatic joints, to represent the time variations of the distance $l_t(t)$ and the pendulum's length $l_p(t)$. Thus, we consider a robotic structure having six joints, with corresponding generalized variables

$$\tilde{q}=\begin{bmatrix}q_1\ q_2\ q_t\ l_t\ q_l\ l_p\end{bmatrix}^{\mathrm{T}}.$$

The last three joints of this robotic structure are considered to be weightless. The last joint is considered to hold a time varying point mass equal to $m_p(t)$. The Euler-Lagrange dynamics of this robotic structure are:

$$\tilde{D}(\tilde{q})\ddot{\tilde{q}}+\tilde{C}(\tilde{q},\dot{\tilde{q}})\dot{\tilde{q}}+\tilde{G}(\tilde{q})=\tilde{u}-J^{\mathrm{T}}(\tilde{q})F \quad (9)$$

where

$$\tilde{u}=\begin{bmatrix}u_1\ u_2\ u_3\ u_4\ 0\ u_6\end{bmatrix}^{\mathrm{T}},\ F=\begin{bmatrix}F_x\ F_y\ 0\end{bmatrix}^{\mathrm{T}}$$

where F_x and F_y are the forces applied by the manipulator on the point mass at the x-axis and the y-axis, respectively, and $J(\tilde{q})$ is the corresponding Jacobian matrix.

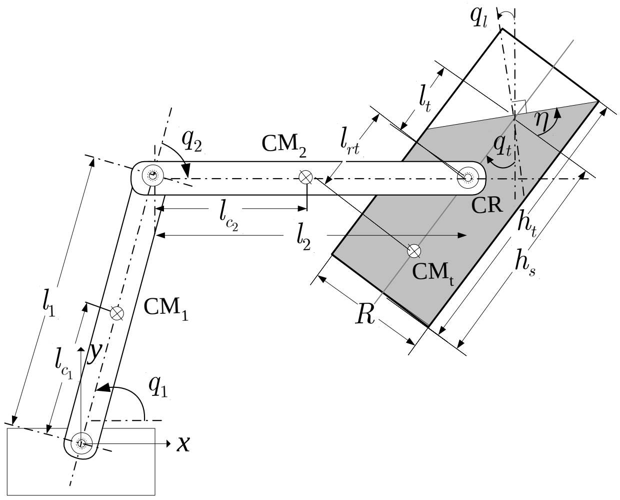

Figure 1. Robotically controlled liquid container ([8],[9])

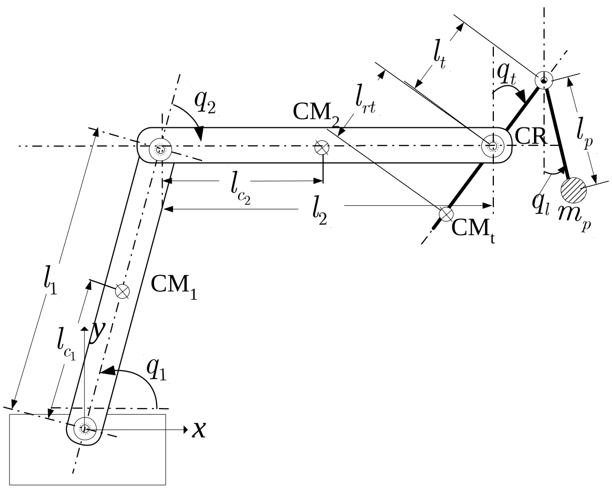

Figure 2. Representation of liquid's motion with a pendulum ([8],[9])

The dynamics of the point mass are given by

$$\frac{d}{dt}\left[m_p(t)\frac{d}{dt}x_m(\tilde{q}(t))\right]=F_x(t)-F_{v,x}(t) \quad (10a)$$

$$\frac{d}{dt}[m_p(t)\frac{d}{dt}y_m(\tilde{q}(t))] = F_y(t) - F_{v,y}(t) - m_p(t)g \quad (10b)$$

where $F_{v,x}$ and $F_{v,y}$ the forces applied on the mass at the x-axis and the y-axis, respectively, due to viscosity, and x_m and y_m the direct kinematics nonlinear functions that determine the coordinates of the point mass on the x-axis and the y-axis, respectively.

Note that u_4 and u_6 represents forces applied by virtual actuators which are supposed to drive the two virtual prismatic joints. These are virtual forces which are considered in order to simulate variation of the parameters $l_t(t)$ and $l_p(t)$ according to (3), (6) and (8). Hence, the corresponding equations in (9) may be ignored.

According to the above and using equations (1)-(3), (6) and (8)-(10), the dynamics of the liquid transfer structure during the outpouring phase may be approximated by a simplified model having the form:

$$\hat{D}\left(q,h_s\right)\begin{bmatrix}\ddot{q}\\ \ddot{h}_s\end{bmatrix} + Q\left(q,h_s,\dot{q},\dot{h}_s,F_{v,x},F_{v,y}\right) = \begin{bmatrix}u\\ 0\end{bmatrix} \quad (11)$$

The second order dynamics of $h_s(t)$ incorporated in (11) are derived by differentiating (6), namely:

Condition 1:

$$\eta(t) = \eta_c(t) \text{ and } \dot{\eta}(t) \geq 0, \ \forall t \in [t_a, t_b]$$

Modeling equation 1:

$$\ddot{h}_s(t) = \frac{R}{2}\left(\frac{-1}{\cos^2\left(\eta(t)\right)}\ddot{\eta}(t) - \frac{2\tan\left(\eta(t)\right)}{\cos^2\left(\eta(t)\right)}\dot{\eta}^2(t)\right),$$
$$\dot{h}_s(t_a) = -\frac{R}{2}\frac{\dot{\eta}(t_a)}{\cos^2\left(\eta(t_a)\right)}$$
$$\forall t \in [t_a, t_b] \quad (12a)$$

Condition 2:

$$\eta(t) < \eta_c(t) \text{ or } \dot{\eta}(t) < 0, \ \forall t \in (t_a, t_b)$$

Modeling equation 2:

$$\dot{h}_s(t) = \ddot{h}_s(t) = 0, \quad \forall t \in (t_a, t_b) \quad (12b)$$

where $\eta = q_l - q_t$ and η_c as defined by (4). Equation (12a) describes the reduction of liquid's height due to liquid's outpouring. This equation is valid at those instants of time at which the liquid's surface reaches the edge of the tank ($\eta(t) = \eta_c(t)$), while tank's tilting and/or liquid sloshing cause outpouring ($\dot{\eta}(t) \geq 0$). Equation (12b) becomes valid at those instants of time at which either the liquid's surface is away from the edge of the tank ($\eta(t) < \eta_c(t)$) or it is on the edge of the tank, but tank's tilting and/or liquid sloshing prevent outpouring ($\dot{\eta}(t) < 0$). Equations (12) constitute a switching model that describes the variation of the liquid's height. The incorporation of (12) in (11) implies that (11) is also a switching model, since the structure of the matrices $\hat{D}$ and Q vary according to (12).

2.4 Design Requirements

The system described in the previous subsections may be used for automatic liquid transfer and pouring in several industrial applications as for example metal casting. The objectives of any control system designed for the outpouring phase of such applications are the following:

I) To achieve sufficiently fast execution of the outpouring task in order to avoid metal cooling and to increase productivity.

II) To control the amount of liquid that outpours into the mold.

III) To avoid liquid sloshing during the outpouring phase, since this may cause outpouring of excessive amounts of liquid or even liquid loss outside the mold.

In the following sections, the design of an automatic control system aiming to achieve these design goals is studied.

3 Control Design

In [8] and [9] a control design scheme comprising a partial inverse dynamics controller with a heuristically tuned PID controller has been proposed to suppress liquid sloshing during liquid transfer, as well as during the forward and backward tilting phases of the pouring process. In the following, a design scheme with similar structure is proposed, which is specifically oriented to serve the design requirements presented in Subsection 2.4, during the outpouring phase of the pouring process. The design scheme exploits measurements of the manipulator links and the container position and velocity variables, but it does not use measurements of the pendulum's position and velocity, which as already mentioned are not considered to be measurable. Lack of measurements of the liquid's motion does not allow to fully linearize the system using an inverse dynamics controller. Thus, the proposed partial inverse dynamics controller is designed to achieve I/O decoupling and feedback linearization in the ideal case where the liquid's surface does not oscillate.

The proposed partial inverse dynamics controller is described by the equation (see also [8] and [9]):

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \bar{C}(\bar{q},\dot{\bar{q}})\dot{\bar{q}} + \bar{G}(\bar{q}) + \bar{D}(\bar{q}) \begin{bmatrix} \ddot{q}_{d,1} + k_1(\dot{q}_{d,1} - \dot{q}_1) + k_2(q_{d,1} - q_1) \\ \ddot{q}_{d,2} + k_1(\dot{q}_{d,2} - \dot{q}_2) + k_2(q_{d,2} - q_2) \\ \ddot{q}_{d,t} + k_1(\dot{q}_{d,t} - \dot{q}_t) + k_2(q_{d,t} - q_t) + k_2 w_3 \end{bmatrix} \quad (13)$$

where $\bar{q} = \begin{bmatrix} q_1 & q_2 & q_t \end{bmatrix}^{\mathrm{T}}$, $w_3(t)$ is an auxiliary input variable,

$$\bar{D}(\bar{q}) = [d_{i,j}([\bar{q}^{\mathrm{T}} \quad 0]^{\mathrm{T}})],\ i, j = 1,2,3$$

$$\bar{C}(\bar{q},\dot{\bar{q}}) = [c_{i,j}([\bar{q}^{\mathrm{T}} \quad 0]^{\mathrm{T}},[\dot{\bar{q}}^{\mathrm{T}} \quad 0]^{\mathrm{T}})],\ i, j = 1,2,3$$

$$\bar{G}(\bar{q}) = [G_i([\bar{q}^{\mathrm{T}} \quad 0]^{\mathrm{T}})],\ i = 1,2,3$$

while $q_{d,1}(t)$, $q_{d,2}(t)$ and $q_{d,t}(t)$ denote the desired trajectories for the first and the second manipulator's joint variables and the tank's rotation respectively.

The partial inverse dynamics controller (13) would achieve linearization and input/output decoupling of the liquid's transfer structure dynamics (7) in the ideal case where the liquid's surface would remain always horizontal ($q_l = 0$) and no liquid outpouring takes place ($\dot{h}_s = \ddot{h}_s = 0$). The controller parameters k_1 and k_2 are selected equal to 11 and 30, respectively [9], so that they would achieve closed-loop stability and sufficiently small settling time in the aforementioned ideal case.

Consider now an additional PID controller that drives the auxiliary input variable $w_3(t)$:

$$w_3(t) = f_1 e_t(t) + f_2 \dot{e}_t(t) + f_3 \int_0^t e_t(\tau) d\tau \quad (14)$$

where $e_t(t) = q_{d,t}(t) - q_t(t)$ and $f_i, i = 1,2,3$ are the controller parameters to be determined. The additional PID controller is applied to suppress sloshing, thus keeping the liquid's level oscillations sufficiently small.

The parameters $f_i, i = 1,2,3$ of the PID controller (14) are determined using a metaheuristic search algorithm introduced in [20], which is appropriately adjusted to meat the design requirements of the pouring task. The metaheuristic algorithm performs repeatedly random search within an appropriate search area, which has the form of a hyperectangle in the controller parameters space. At each repetition of the search, simulation is performed for the linearization of the closed-loop system produced by the application of controllers (13) and (14) to system (7). Linearization is performed around the operating point corresponding to a tilting angle for the container equal to $\eta_{c,0}$. The metaheuristic search algorithm utilizes the simulation results to solve numerically an optimization under constraints problem, that has been determined in [9].

The application of the metaheuristic optimization algorithm presented in [9], resulted in the determination of a PID controller of the form (14) with

$$f_1 = 1.8566,\ f_2 = 2.4191,\ f_3 = 0.5634.$$

4 Simulation Results

In the following, the performance of the proposed control scheme is illustrated through simulation results derived from its application to the nonlinear system (11).

The parameters of the considered liquid transfer structure are given in Table 1.

NOMENCLATURE		
Parameter	Value	Physical Meaning
m_1, m_2	10[kg]	Mass of the 1st, 2nd link [24]
l_1, l_2	1[m]	Length of the 1st, 2nd link [24]

I_1, I_2	$2[\text{kg}\cdot\text{m}^2]$	Moment of inertia of the 1st, 2nd link [24]
l_{c1}, l_{c2}	$0.5[\text{m}]$	Distance of the 1st, 2nd link's center of mass from the 1st, 2nd joint [24]
m_t	$1.68[\text{kg}]$	Tank's mass
$l_{t,0}$	$0.053[\text{m}]$	Nominal distance between the tank's center of rotation (CR) and the free surface of the liquid
l_{rt}	$0.1[\text{m}]$	Distance of the tank's center of mass (CM) from the center of rotation (CR)
I_t	$7.193\cdot 10^{-3}$ $[\text{kg}\cdot\text{m}^2]$	Tank's moment of inertia
R	$0.14[\text{m}]$	Distance between the walls of the tank [1]
h_t	$0.17[\text{m}]$	Height of the tank
$h_{s,0}$	$0.16[\text{m}]$	Initial liquid level [1]
$m_{p,0}$	$3.136[\text{kg}]$	Initial pendulum's mass [1]
$l_{p,0}$	$0.0446[\text{m}]$	Initial pendulum's length [1]
c	$1.88[\text{N}\cdot\text{sec/m}]$	Liquid coefficient of viscosity [1]
g	$9.81[\text{m/sec}^2]$	Gravity acceleration

Table 1. Parameters of the liquid transfer structure

To illustrate also robustness of the proposed scheme, the values given in Table 1 for the initial values $m_{p,0}, l_{t,0}, l_{p,0}$ and $h_{s,0}$, before the initiation of liquid outpouring, are selected different from the corresponding used in [9]. More specifically, in [9] the PID controller was tuned considering that

$$h_s = 0.14[\text{m}],\ m_p = 2.744[\text{kg}],$$
$$l_t = 0.033[\text{m}]\ \ l_p = 0.0442[\text{m}].$$

The initial conditions for the state variables of system (11), are considered to be:

$$q_1(0\text{-}) = \pi/2[\text{rad}],\ q_2(0\text{-}) = -\pi/2[\text{rad}],$$
$$q_t(0\text{-}) = -\eta_{c,0} = -0.1419[\text{rad}],\ q_p(0\text{-}) = 0[\text{rad}],$$
$$\dot q_1(0\text{-}) = 0[\text{rad/second}],\ \dot q_2(0\text{-}) = 0[\text{rad/second}],$$
$$\dot q_t(0\text{-}) = 0[\text{rad/second}],\ \dot q_p(0\text{-}) = 0[\text{rad/second}],$$
$$h_s(0-) = h_{s,0} = 0.16[\text{m}],\ \dot h_s(0-) = 0[\text{rad/sec}].$$

These initial conditions imply that the liquid's surface is at the edge of the tank.

The external commands that drive the joints of the robotic manipulator aim to keep the robot's end-effector at its current position, thus $q_{d,1}(t) = \pi/2[\text{rad}]$ and $q_{d,2}(t) = -\pi/2[\text{rad}]$ for $t \geq 0$. The external command for the tank's rotation is selected equal to the following sigmoid function that corresponds to reduction of the liquid height at the final value $h_{s,f} = 0.14[\text{m}]$ and corresponding reduction of the liquid's mass to the final value $m_{p,f} = 2.744[\text{kgr}]$:

$$q_{d,t}(t) = -0.1418 - 0.2631(1 - e^{-t} - te^{-2t} - 1.5t^2e^{-3t} - 2.66t^3e^{-4t} - 5.21t^4e^{-5t})$$

Based on [1], [3] and [5], the simulation results are derived considering that the forces acting on the point mass due to viscosity are given by $F_{v,x} = -cl_p(t)\cos(q_l)\dot\eta$ and $F_{v,y} = 0$, where c the equivalent viscosity coefficient. Components of viscosity forces which may be due to the variation of the liquid's level l_p are considered to be neglectable. This is also supported by the simulation results according to which the variations of l_p are very small. Note also that simulations made considering the viscosity force to be perpendicular to the pendulum's link, instead of horizontal, appear no significant differences.

The simulation results are presented in Figures 3-12. Figures 3 and 4 present the closed-loop trajectories for the two first joints. It is obvious from Figures 3 and 4 that the motion of the tank and the liquid, as well as the reduction of liquid's mass practically has no effect on the positioning of the manipulator's end-effector. Figure 5 presents the closed-loop trajectory for the tank's rotation, while Figure 6 illustrates the variable $\eta(t)$. Figure 7 illustrates the variation of the liquid's height $h_s(t)$. As it follows from Figure 7, the reduction of the liquid's level and equivalently the reduction of the liquid's mass are equal to the desired ones. Hence, liquid sloshing has not resulted in excessive outpouring. Moreover, according to the simulation results the variation of the pendulum's equivalent length $l_p(t)$ is very small, which implies that the values of $h_s(t)$ remains within the saturation area of the function that determines the natural frequency and consequently the equivalent length of the pendulum (see equations (2) and (3)).

5 Conclusions

In the present work, a simplified nonlinear model for the outpouring phase of the pouring process has been derived, for the case of a liquid container carried by a manipulator. The performance of a two stage control design scheme on the control of liquid outpouring and the suppression of liquid sloshing during the outpouring phase has been studied. The proposed scheme, that does not require measurements of the liquid's motion within the tank, combines a partial inverse dynamics controller with a PID controller, tuned with the use of a "metaheuristic" search algorithm. Both controllers are designed ignoring the loss of liquid's mass due to outpouring. The controller performance has been studied using simulation results.

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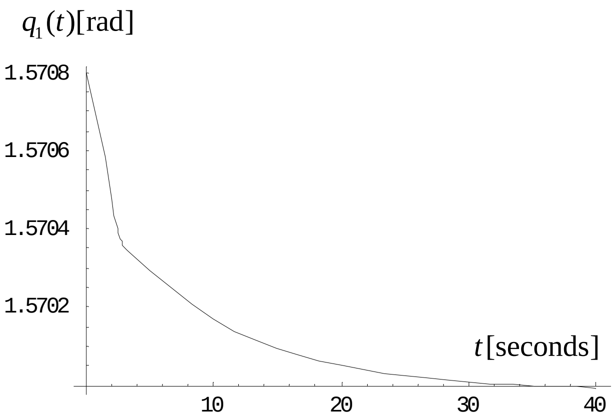

Figure 3. Closed-loop values for $q_1(t)$

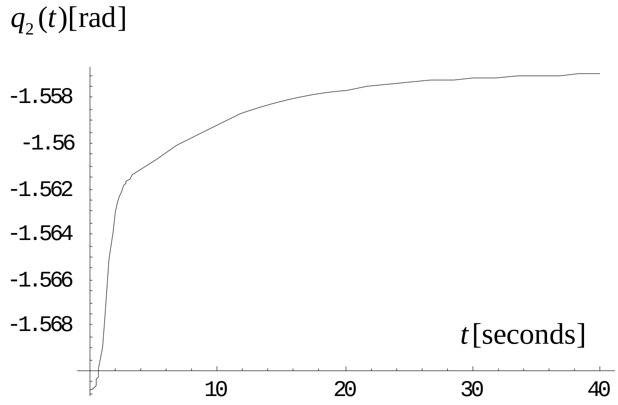

Figure 4. Closed-loop values for $q_2(t)$

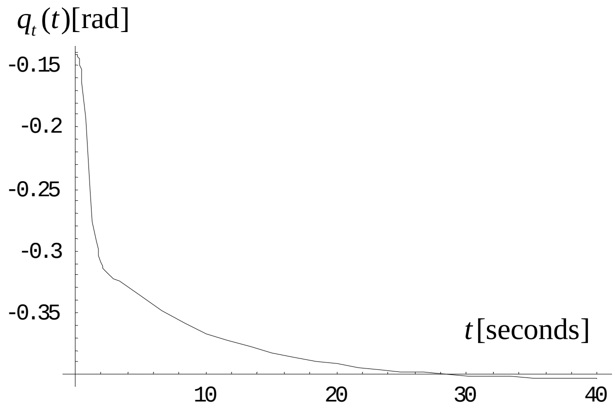

Figure 5. Closed-loop values for $q_t(t)$

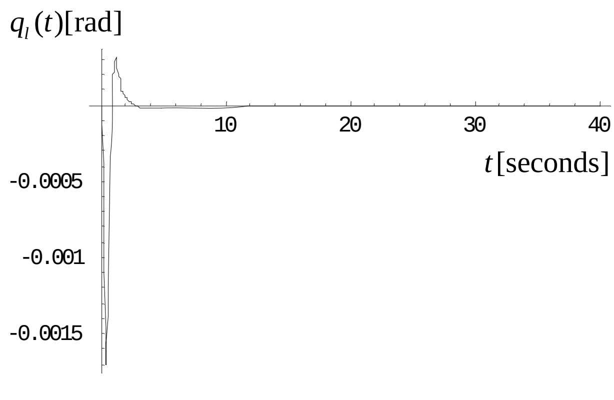

Figure 6. Closed-loop values for $q_l(t)$

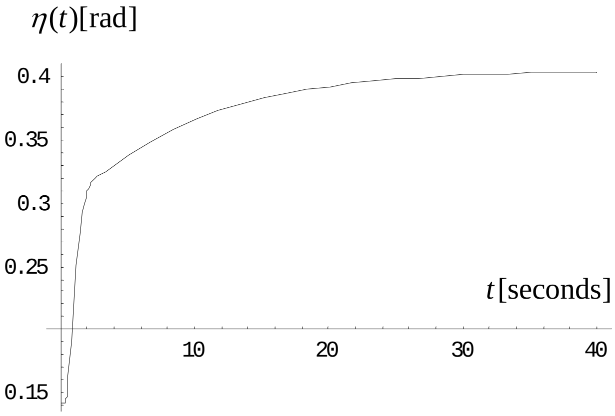

Figure 7. Closed-loop values for $\eta(t)$

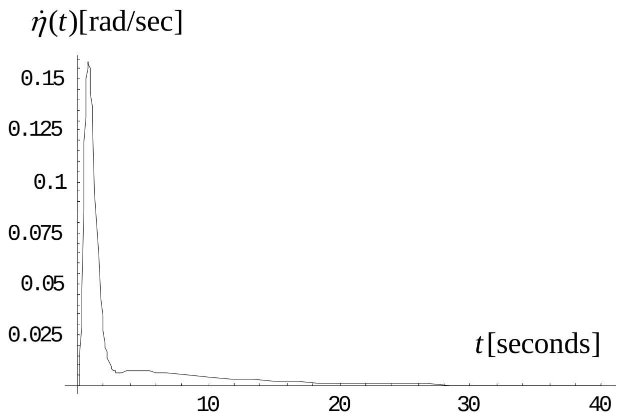

Figure 8. Closed-loop values for $\dot{\eta}(t)$

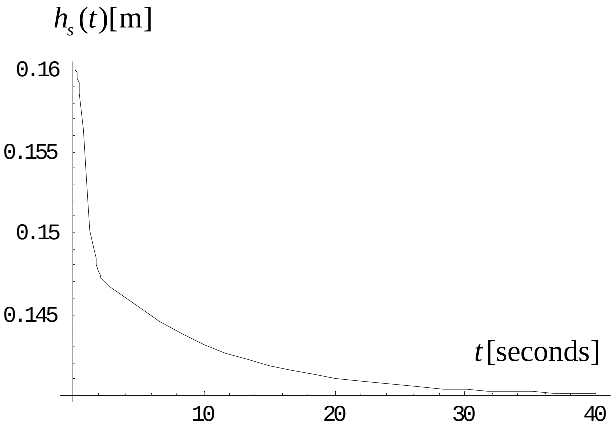

Figure 9. Closed-loop values for $h_s(t)$

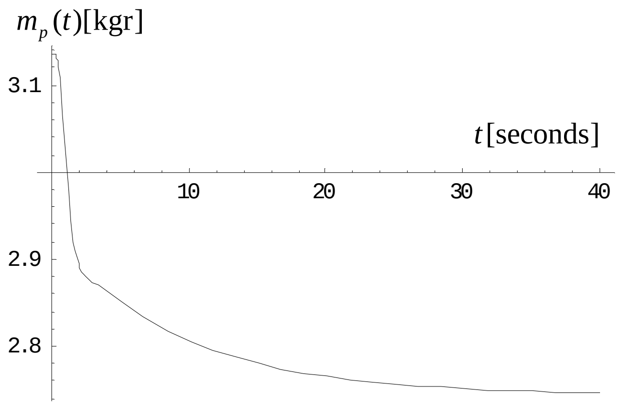

Figure 10. Closed-loop values for $m_p(t)$

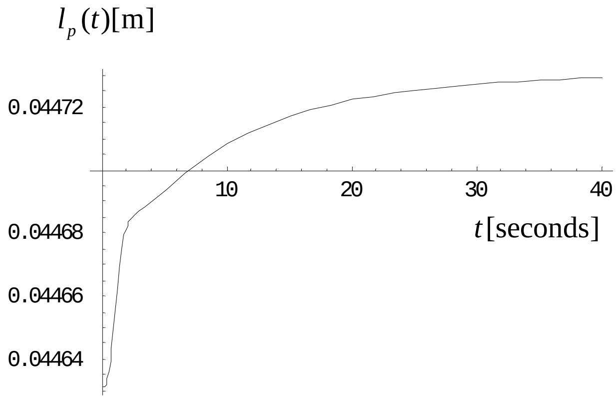

Figure 11. Closed-loop values for $l_p(t)$

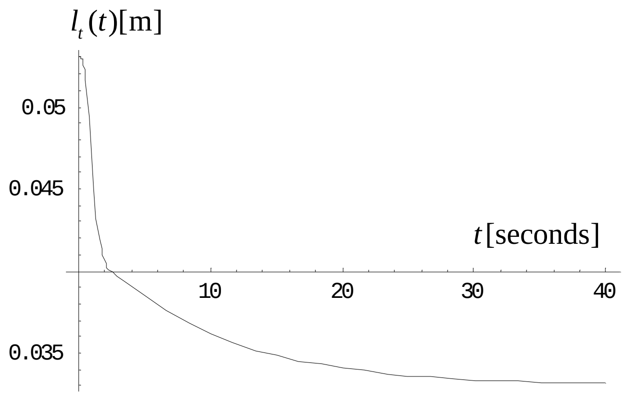

Figure 12. Closed-loop values for $l_t(t)$

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