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Manipulating liquids with robots: A sloshing-free solution

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ABSTRACT

This paper addresses the problem of suppressing sloshing dynamics in liquid handling robotic systems by an appropriate design of position/orientation trajectories. Specifically, a dynamic system, i.e. the exponential filter, is used to filter the desired trajectory for the liquid-filled vessel moved by the robot and counteract the sloshing effect. To this aim, the vessel has been modelled as a spherical pendulum of proper mass/length subject to the accelerations imposed by the robot and the problem has been approached in terms of vibration suppression to cancel the residual oscillations of the pendulum, i.e. the pendulum swing at the end of the reference rest-to-rest motion. In addition, in order to reduce the relative motion between liquid and vessel, an orientation compensation mechanism has been devised aiming to maintain the vessel aligned with the pendulum during the motion.

The effectiveness of the proposed approach, both in simple point-to-point motions and complex multi-point trajectories, has been proved by means of an exhaustive set of experimental tests on an industrial manipulator that moves a cylindrical vessel filled with water.

This innovative solution effectively uses all the degrees of freedom of the robotic manipulator to successfully suppress sloshing, thus significantly improving the performances of the robotic system. Furthermore, the proposed solution, showing a high degree of robustness as well as intrinsic design simplicity, is very promising for designing novel industrial robotics applications with a short time-to-market across key manufacturing sectors (e.g., food and beverage, among others).

1. Introduction

As the current industrial scenario becomes increasingly competitive, modern manufacturing systems must comply with strict, demanding functional requirements. In this context, industrial automation plays a key role in optimizing manufacturing processes and maximizing production efficiency and flexibility, while reducing waste and energy consumption. As a consequence, industrial robotics is pervading non-traditional industrial sectors to overcome the severe and unacceptable limitations due to the use of rigid automation systems. The resulting novel use of industrial robots in non-traditional industrial sectors has created new challenges that have attracted the attention of scientists and technologists.

One of these key challenges is the use of robot manipulators to handle liquid materials. A particularly interesting and promising case is the use of industrial robots in the food processing industry to accomplish complex tasks – i.e., moving, manipulating, pouring liquid ingredients (see Nair (2017)) – traditionally executed by human operators or by means of process control systems. In light of this, research in this area is gaining growing importance driven by the food and beverage industry needs to increase production performances, dependability and flexibility. For the same reasons, many other industrial sectors could benefit from an effective solution to this problem. As an example, the steel industry could address the problem of handling melted metal by means of industrial robots (see Aribowo, Yamashita, and Terashima (2015) and Aribowo, Yamashita, Terashima, and Kitagawa (2010)).

These industrial cases can be solved by addressing the general problem of controlling a robotic manipulator to move a liquid-filled vessel without spilling. This problem is highly challenging due to the complexity of nonlinear fluid dynamics that arises within the vessel when this moves along a generic 3D trajectory. In particular, the liquid slosh dynamics – i.e., flows occurring when free surface waves are generated inside a tank – are extremely detrimental to industrial application performances and very complex to counteract.

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Scientific literature has put forward a number of theoretical approaches to mathematically describe and analyse slosh dynamics (see Abramson (1966) and Ibrahim (2005) among others). Particularly, in relation to the automatic machinery sector, many solutions have been proposed to avoid sloshing flows when moving liquid-filled containers. Results presented in Consolini, Costalunga, Piazzi, and Vezzosi (2013), Hamaguchi and Taniguchi (2002, 2009) and Yano and Terashima (2001) are a significant sample of existing solutions. All the methodologies used in these studies rely on the assumption of a simplified linear model of the slosh dynamics, and sloshing is tackled as a model-based disturbance suppression problem that can be solved by means of proper feed-forward or feedback control architectures. In particular, feed-forward methods, which generate a proper reference trajectory for the machine, are of industrial interest, due to their ease of implementation on standard industrial machines and their use of a reduced sensor apparatus. In addition, it is important to stress that the majority of these studies consider simple one-dimensional motions, and, even when 3D motions are introduced, the slosh phenomenon is decoupled along the different motion axes and treated as a set of independent problems (see Chen, Hein, and Worn (2007) and Yano and Terashima (2005)). Finally, when multi-degrees-of-freedom robotic manipulators are taken into consideration, the possibility of changing both the position and the orientation of the vessel – as described in Aribowo et al. (2015) and Moriello, Biagiotti, Melchiorri, and Paoli (2017) – is generally ignored, despite the fact that the compensation of slosh dynamics via tilt angle modification has been proved in many papers, such as Chen et al. (2007) and Feddema et al. (1997).

This paper presents an innovative feed-forward method to effectively reduce slosh dynamics in liquid handling robotic systems. This method has been widely tested both in simulation and experimentally. The innovation of the proposed solution comes from a proper combination of two control actions: one is aimed at generating a filtered translational trajectory able to reduce the linear acceleration responsible for the sloshing, while the other adds to it by properly controlling the dynamical 3D orientation of the vessel. The theoretical machinery used to filter the vessel acceleration is based on the use of an exponential smoother (see Biagiotti, Melchiorri, and Moriello (2015)) that guarantees the required degree of continuity of the trajectory.

The effectiveness and robustness of the proposed solution proved by experimental tests, as well as its intrinsic design simplicity and ease of implementation, make this approach particularly promising for designing novel industrial robotics applications with a short time-to-market across key industrial sectors, e.g., food and beverage manufacturing.

The paper is organized as follows. In Section 2, the mathematical modelling of the slosh dynamics is briefly reviewed and an equivalent mechanical model is derived. In Section 3, the proposed solution is devised and thoroughly discussed. Finally, in Section 4 an exhaustive set of experimental results is proposed, proving the validity, effectiveness and robustness of the approach.

A preliminary version of this paper was published in the proceedings of the 2017 IEEE International Conference on Robotics and Automation (ICRA) (Moriello et al., 2017).

2. Mathematical model of the slosh dynamics

This section aims to derive a mathematical model for the sloshing waves generated inside a liquid-filled vessel that moves along a 3D trajectory. This is a particularly complex problem that can be handled linearizing the Navier–Stokes equations, thus obtaining a linear model that represents the superposition of j different sloshing modes. This topic is thoroughly discussed in Ibrahim (2005), which the present paper builds on.

This paper deals with the case of a fluid in a cylindrical vessel; however, vessels with different geometrical shapes can also be considered by simply extending the methodology.

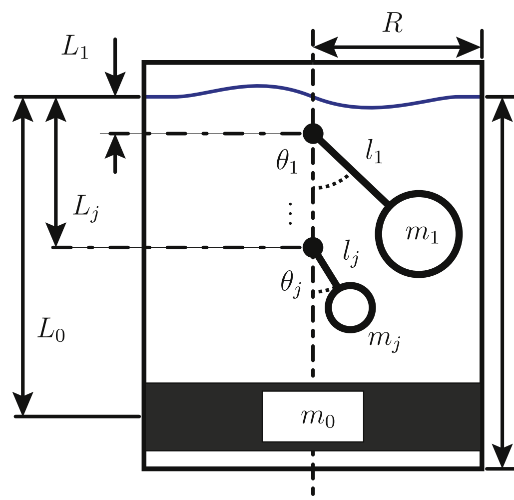

Fig. 1. Equivalent mechanical model approximating the liquid dynamics in a cylindrical vessel.

With regard to a cylindrical vessel, the natural frequency of the jth sloshing mode is

$$\omega_{nj} = \sqrt{\frac{g\,\xi_j}{R}\tanh\left(\frac{h\,\xi_j}{R}\right)} \tag{1}$$

where g is the gravity constant, R is the cylinder radius, h is the liquid height, and ξ_j is the jth root of the derivative of the Bessel function of the first kind. Furthermore, the damping coefficient δ_j of the jth generic sloshing mode can be derived observing how the sloshing waves lessens according to a logarithmic decay ratio due to energy dissipation. For control purposes, it is a common practice to take into account only the first asymmetric mode, which is dominant with respect to higher modes. In this case, the damping ratio is usually defined by means of an empirical relationship (see Abramson (1966)) which takes into account the kinematic viscosity ν of the fluid and the vessel parameters h and R:

$$\delta_1 = \frac{2.89}{\pi}\sqrt{\frac{\nu}{\sqrt{R^3 g}}}\left[1 + \frac{0.318}{\sinh(\frac{1.84h}{R})}\,\frac{1-\frac{h}{R}}{\cosh(\frac{1.84h}{R})}\right]. \tag{2}$$

This linear model defines a mechanical system that approximates the liquid dynamics in a moving vessel. The equivalent model consists of a rigid mass m_0 and a series of pendula with mass m_j, length l_j, and support point located at a distance L_j from the undisturbed free surface of the liquid. Fig. 1 depicts this mechanical system.

Since the equivalent mechanical model must preserve the mass and the momentum of inertia of the liquid, as well as possess the same modes of oscillations as the original system, a set of relations between the physical parameters m_j, l_j, L_j and the modes characteristics ω_{nj} and δ_{nj} can be derived (see Ibrahim (2005)). As an example, the pendulum relation $\omega_{nj} = \sqrt{g/l_j}$ allows to derive the length l_j. These relations, here omitted for the sake of brevity and clarity, show that the values of L_j are rather small, and consequently the pivots of the pendula lie near the liquid surface. In addition, both the lengths l_j and masses m_j rapidly decrease as the index j grows. In view of this result, this paper proposes a simplified model of the slosh dynamics. Specifically, this simplified model only describes the first asymmetric mode of the slosh by means of a single pendulum with mass m_1, length l_1 and pivot located at the centre of the liquid surface. Moreover, the pendulum is assumed to be always orthogonal to the liquid surface that is supposed to be planar. Based on this assumption, the pendulum angle θ_1 measures the angle between the liquid surface and the horizon. Fig. 2 illustrates this simplified mechanical model.

When the liquid-filled vessel is moved by a robotic manipulator, the effect of the 3D motion on the pendulum pivot needs to be modelled.