MODELLING OF A HYDRODYNAMICALLY ACTUATED MANIPULATOR BASED ON 3-D STRIP THEORY

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ABSTRACT

In this paper, mathematical modelling based on strip theory of the Hydrodynamically Actuated Manipulator (HAM) is proposed to use it for analysis and control synthesis (see Figure 1). A set of Nonlinear Ordinary Differential Equations (ODEs) describes the behaviour of the HAM. First, considering the Euler-Lagrange methodology, the motion of the $R \perp R \parallel P$ manipulator is obtained. Then, a Newtonian approach is used to add the effects of a constant velocity flow of 1 m/s surrounding the 3-DOF manipulator. In order to describe this interaction, each link of the manipulator affected by hydrodynamic forces is discretized using small elements. Each element's contribution is combined to obtain the net acceleration of each link of the HAM. In order to qualitatively validate the model, a set of simulations are performed. Each simulation consists of a comparison between the Lagrangian of the 3-DOF manipulator and its motion when is affected by each added hydrodynamic force.

As in the wheel of inertia, cart-pendulum, or pendubot [1], the hydrodynamically actuated manipulator may be used as an interesting testbed for analysis and control synthesis because it can be seen as two interacting dynamic systems: a fluid and a solid [2]. There are some features that make this manipulator an interesting test bed for analysis and control synthesis. First, the manipulator by itself could be analyzed as an inverted pendulum that moves with a force caused by a fluid [3]. Depending on the position of the reference frame, there will be gravity-bounded nonlinear terms affecting the behaviour of the system. Second, considering the effects of fluid on the solid, nonlinear quadratic dynamics will affect the mechanical system (*e.g.*, [4, 5]). Considering the hydrodynamically-actuated mode of operation of the manipulator, the variable θ will be controlled using the hydrodynamic force of the water through the length of the hydraulic cylinder λ and the angular position of the wing-shaped link γ. Figures 1 and 2 show a sketch of the robot, where l_0 is the distance from the platform of the manipulator to the centre of mass of the hydraulic actuator, and l_1 denotes half of the span of the wing. θ is the angle between the axis x and the axis y'. λ is the distance from the centre of mass of the hydraulic actuator to the centre of mass of the wing along axis x'. γ is the angle between the axis z and the axis x'. Third, non-collocated dynamics will also affect the behaviour of the entire system because of the hydrodynamically-actuated operation mode, which is very interesting for control design purposes (see [6]).

The effect on the underwater manipulator is modelled in a simplified way assuming the flow to be irrotational, incompressible, and laminar (see for instance [5] and [7] and the references therein). We incorporated an added mass term to model the effect of displaced water, which is calculated as the force/moment needed to accelerate the fluid. This term depends on the displaced volume of the fluid and its density (see for instance [8]). The hydrodynamic force on the body dependent on the relative velocity is decomposed in two forces, orthogonal to each other, called the drag force and the lift force. The hydrodynamic added inertia and drag/lift coefficients are commonly computed from the strip theory coming from the potential flow background for 2-D inviscid flows and extended semi-empirically to three dimensions (see [2] and references there in).

A half-scale model, which preserves all the main characteristics of the full scaled model, has been used for modelling, analysis and control synthesis. To model the manipulator under water, the hydrodynamic forces affecting it were added one by one considering a Newtonian approach. Some terms were neglected due to

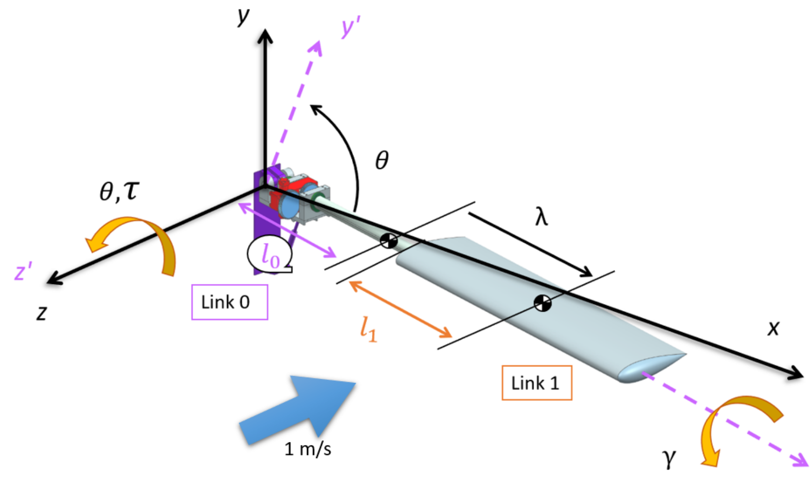

Fig. 1. The 3-DOF mechanical manipulator.

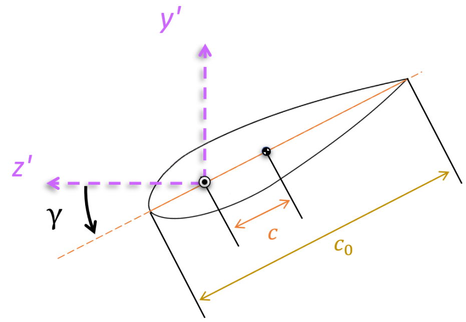

Fig. 2. The wing-shaped link of the manipulator.

their small contribution to the model based on a worst case scenario. To verify the validity of the model, several numerical simulations were considered first on the basic Lagrangian model and then comparing this to the model affected by each of the different hydrodynamic effects. Each series of numerical open-loop numerical experiments was performed with different initial conditions for the manipulator or different conditions for the flow. With each experiment, the system's behaviour was confirmed by observing the behaviour followed basic principles. Although the fidelity of the model may only be verified through lengthy Computational Fluid Dynamics (CFD) experiments or costly physical experiments, the proposed model is believed to replicate enough of the effects to allow for studies on controls to be performed.

Keywords: modelling; nonlinear systems; Euler-Lagrange.

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