Legged Locomotion Models in the Aquatic Domain

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I. BACKGROUND

Nearly all primarily terrestrial animals have the ability to locomote in aquatic environments by adapting their in-air joint motions to create on/under water swimming or underwater walking. This modal flexibility significantly improves their ability to traverse the natural world unhindered. Currently terrestrial legged robots are generally unable to employ similar aquatic behaviors. Many challenges exist in enabling legged robots to operate effectively in the aquatic domain, including the lack of simplified multi-modal dynamic models which can be used for parameter tuning, behavioral prediction, and control (such as SLIP [1] in the terrestrial domain and the Full-Goldman model [2] in the scansorial domain). Here, we approach the task of creating unified models, which capture locomotion in swimming as well as of these domains, by expanding on existing templates of legged locomotion.

II. METHODS

We developed two new models to capture the dynamics of limbed swimming (Fig. 1A-C): one in the saggital plane and one for sprawled posture surface swimming in the lateral plane. The equations for these models are derived via Newton's method and incorporate all the forces existing in the SLIP and point mass FG model respectively. The fluid effects are similarly modeled using simplified (force-based) expressions of drag, lift, buoyancy, and added fluid mass.

The saggital plane model expands from both the body centered hydrodynamic forces of the U-SLIP model [3] and the leg centered hydrodynamic drag of the VM-SLIP model [4], by including all of the forces from these models as well as leg lift force, torsional compliance, and additional adjustments for operating at fluid interfaces that were not included in the earlier models. The lateral plane model is designed for surface swimming and only incorporates hydrodynamic effects of drag and added mass on the hands and body. Propulsion in this model is generated by disengaging the hands from the fluid on the reset stroke, similar to detachment from the substrate in the climbing model. Numerical integration techniques were able to find stable period-1 limit cycles using feed-forward controllers.

III. RESULTS

In the saggital plane, by varying only the buoyancy (via body radius) and angular actuation magnitude, gaits were found for terrestrial hopping, underwater hopping, and surface paddling (shown Fig. 1D for three strides) *using the same model*. In the lateral plane, limit cycles for both surface swimming, Fig. 1E, and vertical climbing were found with the same model.

Examples of results which have been obtained using these new models include: matching published data on Labradors to fast efficient swimming strategies, and inspiring the design of the first robot capable dynamic vertical climbing and swimming.

REFERENCES

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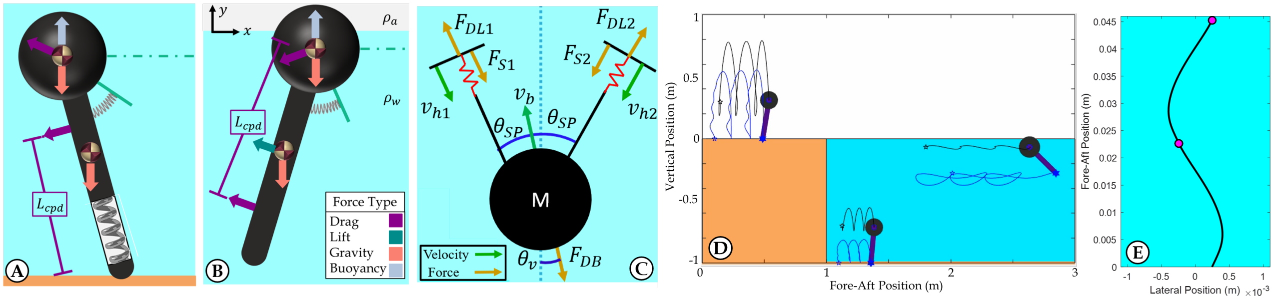

Fig. 1: Modified aquatic models: the Fluid Field Spring-Loaded Inverted Pendulum (FF-SLIP) model in stance (A) and flight/swim (B) and the lateral plane swimming model (C). Limit cycles found in the saggital (D) and lateral (E) planes.