2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Design of an Omnidirectional Propulsion System for Small Jet-Boats

David Foley and Jean-Sebastien Plante
Department of Mechanical Engineering
Universite de Sherbrooke

Abstract— **Jet-boats perform remarkably well at high-speed but lack low speed maneuverability for tight maneuvers such as ducking. This paper presents a low speed omnidirectional propulsion system controlled with a joystick for jet-boats. Two concepts are presented and evaluated. The first concept uses all original parts. The second concept uses a set of fix jet nozzles disposed around the hull. The position and angles of the nozzles are optimized with an index of omnidirectionality quality based on the projection of a set of force solutions on a shell with the shape of the desired force space. A 3D simulator backed by experimental results serves for the evaluation by potential customers of each design. The first concept exhibited poor maneuverability, as it offers ten times less force in sway than in surge. The optimized force space of the second concept is much more uniform, and was unanimously appreciated for its quality of low speed maneuverability. Both designs have been validated experimentally. The present work offers an omnidirectional propulsion system that is easy to enhance with advanced control laws. Velocity feedback control is given as example, and shows important improvement of maneuverability and robustness to miscalibration.**

I. INTRODUCTION

Jet-boats are designed for high speed operation, often at the expense of low speed maneuverability. Yet, ducking in a busy marina requires precise maneuvers that must inevitably be performed with such boats. These operations may be stressful and difficult for less accustomed users. Maneuverability can be enhanced if the pilot uses an intuitive omnidirectional propulsion system commanded with a joystick, such as proposed in this paper. The push and twist of the joystick commands the corresponding force on the boat. The availability of GPS and compass on board make it possible to enrich the system with features of pilot assistance at virtually no additional costs.

A popular omnidirectional propulsion solution is to add bow and stern electric thrusters [1]. This solution requires an additional high power electric system and ends up costly. The present project seeks a concept that uses mechanical power already available on-board.

Omnidirectional propulsion systems using readily available power source are available in some high end sport boats from Mercury [2] and Volvo [3]. These systems work by controlling independently the direction of the two propellers at the rear of the boat. However, to the authors knowledge, no such features have been proposed on sport-boats propelled by water-jets.

The purpose of the project is to design an intuitive and affordable system that adds a feature of omnidirectionality on water-jet propelled sport boats for low speed maneuvers. Two propulsion systems are presented. The *two-jets concept* uses all original parts, consisting of direction nozzles and reversing cups, to provide a simple and low cost system. The *multi-jets concept* redirects the flow of the pump to many jet nozzles distributed around the hull. An analytical model is developed and used to optimize the performance of each concept. Simulations backed by experimental results showed that both concepts are viable, but the improved force space shape of the multi-jets concept, provided by the multi-jets concept, has superior omnidirectional propulsion.

A. System Overview

Figure 1 shows an overview of the control system used to command forces on the boat directly from a joystick. The critical element of this chain is the *Inverse Propulsion Model* box, which finds the states of the actuators that will generate the commanded force.

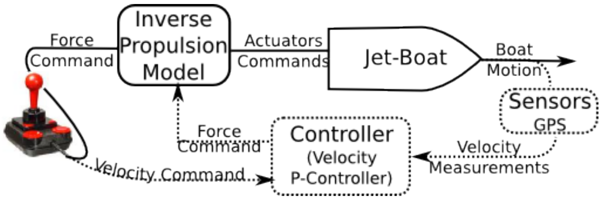

Fig. 1. Overview of the control system

The propulsion model of the boat predicts the force as a function of the state of the mechanical parts around the water-jet. Propulsion from water-jet is fairly accurately calculated with a momentum control volume [4]. The flow in the pump can be approximated from dimensionless pump theory or CFD calculation [5]. Experimental measurements have been conducted for a variety of pumps [6], but none was done on a pump similar to the present one in the project. Moreover, for the two-jets concept, the effect of the direction nozzle and reversing gate was not accurately predictable from models. Experiments were therefore conducted to characterize the pump flow and the effects of the direction nozzle and reversing gate.

For the simulator, the kinetic is approximated with a simple linear boat model. A planar rigid body approach was deemed sufficient since the product is not meant for bad weather conditions that would have significant 3D effects. Hydrodynamic coefficients for kinetic model are typically obtained from scaling laws on model boats and from CFD calculation. Full-scale ship is rarely used [7], but the boat for

978-1-4244-5040-4/10/$26.00 ©2010 IEEE

the project being small, the parameters are identified directly from experiments run on the full-scale boat.

The focus of the project is on providing good open-loop force control. Open-loop is an important fail-safe mode for the frequent case of GPS signal loss, or compass failure. It is also a solid basis to easily produce more advanced control. Therefore, at first, the feedback is the pilot's reaction to the boat's motion. The second step is to implement more advance control, and take advantage of the available on board GPS and compass. Velocity control with GPS and compass measurements is added in dash-line in Fig. 1 as an example.

The propulsion model with parameters from literature is not precise enough for an accurate open-loop control. Off-line calibration of the model parameters is therefore executed from experimental force measurements. On-line calibration would be possible with position measurements, but the sensors and kinetic boat model are additional sources of errors.

B. Omnidirectional Systems Concepts

Two-jets Concept: The two-jets concept works from the original mechanical parts, and this has an advantageous ease of integration with minimal costs. Fig. 2 represents the mechanical parts to control: a direction nozzle and a reversing cup on each of the two pumps. All parts are independently controlled with electric actuator. Engine speed is controlled via CAN Network.

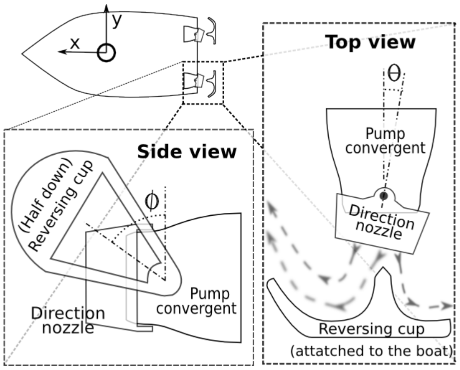

Fig. 2. Two-jets concept : original mechanical parts

Multi-jets Concept: The multi-jets concept uses a set of fix jet nozzles disposed around the hull to provide an improved force space shape, particularly when compared to the two-jets concept which, as shown later, has a limited sway force. Figure 3 is a schematic representation of the concept. The reversing cup is replaced by a valve that redirects a variable part of the flow in a system of two pipes, each of them also with a valve. The nozzles terminating the pipes are at a fix position and angle. The idea is to position the nozzles so that the control over the six valves and the two engines' speed produce a force space with the best possible omnidirectionality. In this project, nozzle positions are optimized with Genetic Algorithm (GA) method. GA based methods have been successful in related works, such as optimal ship hull design for particular economics constraints [8].

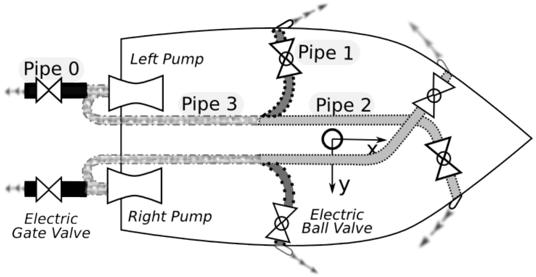

Fig. 3. Multi-jets concept : flow redirected in nozzles

C. Design Requirements

The performance of leisure product such as jet-boats is expressed by how much the client enjoys driving the boat in representative environmental conditions. Clients appreciation in design iterations was considered from trials conducted on a 3D game-like simulator. The simulations allowed confirming engineering specifications such as actuators precision and controller strategies. The effects of wind, current and noise disturbance were also evaluated. The following requirements have been used to design the two concepts:

- Maximum actuators time to travel the full range is around 1.5 second. Slower actuation has a lag that creates oscillations with pilot feedback.
- Sway and Surge force are 700 N, for good controllability in typical wind and current conditions.
- Force space (as defined in section II-A) has a centered ellipsoid shape for good omnidirectional behavior.
- Sway and surge force must be independent and accurate, has it plays a central role in the impression of quality

II. ANALYTICAL DEVELOPMENT

Propulsion models are developed for each concept. They calculate the force on the boat as a function of the actuators' state. For control purpose, the inverse problem is sought, and numerical methods are used to obtain the mechanical states as a function of the desired force.

The boat's frame of reference, Fig. 4, is used for force calculations. The origin is located at the center of mass. The controllable degrees of freedom are surge (x-axis translation), sway (y-axis translation), and yaw (z-axis rotation). Angle, represented by ϕ in Fig. 4, is measured from the x-axis in the positive z-axis rotation.

A. Force Space

The set of all possible control forces is the outcome of all possible combinations of the actuators states in their range of use. The discrete set of possible forces is represented in a 3D space in terms of forces in the x and y axis, and moment in the z axis. As shown in Fig. 5, an ellipsoid, nearly a sphere, is the targeted shape of force space for omnidirectional behavior of the propulsion system, since thrust is then available in all direction (surge, sway, and

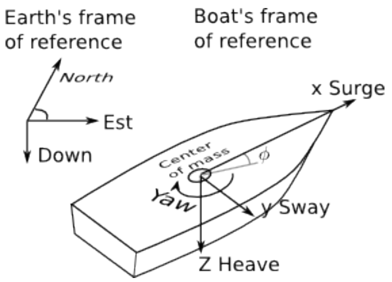

Fig. 4. Boat's frame of reference

yaw) with similar strength. The propulsion model is used to generate the force space of each concept.

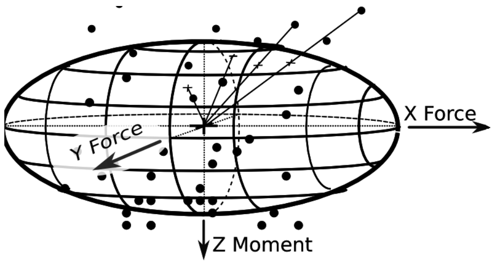

Fig. 5. Design of the cost function

B. The Inverse Propulsion Model

The propulsion model calculates the force on the boat as a function of the actuators' state. However, the problem must be reversed: a force is desired and the actuators' state to produce this force are sought. The inverse problem does not have the property of unicity, since multiple solutions of actuators' state exist for a same desired force. Hence, an additional condition is necessary to select only one combination of actuators. This condition is to minimize the highest of the engines' speed, so to minimize the noise level.

The problem inversion would be very hard or impossible to solve analytically. Instead, the discrete force space is generated and a set of points is selected around the target force. The point with the lowest maximum rpm is the initial guess of a downhill simplex algorithm with the goal of minimizing engine speed, and the constraint of generating the commanded force. The constraint is implemented as a penalty factor on the cost function:

$$Cost = (\|\overline{F_{desired}} - \overline{F_{actual}}\|\beta + 1) * (N_H - N_{min}) \quad (1)$$

where N is engine speed, N_H is the highest of left and right engine speed, $\overline{F}$ is the force vector on the boat, and β is a weighting to bring force and engine speed on a similar scale of importance. A very high cost is given whenever the bounds of the actuators are not respected.

The propulsion model is inverted for a set of forces that spans the region of possible joystick command. The resulting engine speed and valve openings are recorded in a map that serves as a look-up table for open-loop force control.

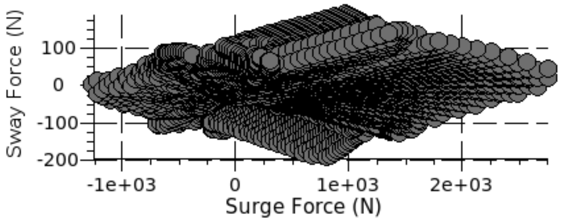

Fig. 6. Slice of the discrete force space of the two-jets concept (between -80 Nm and 80 Nm)

C. Model Specific to the Two-jets Concept

The two-jets concept controls the original parts, which are direction nozzles and reversing cups (Fig. 2). The total propulsion force produced by each pump is a function of engine speed, direction nozzle angle, and reversing cup position.

1) Propulsion Model: An empirical model is defined with an instrumented truss installed between the boat and a fixed dock. One pump at the time, the engines' speed, angle of nozzle, and reversing cup angle are swept through all their combinations over their range of operation. A piecewise polynomial is fitted on the data of force to make a continuous empirical propulsion model. Additional measurements with the two engines running together show that the force variation due to interaction between the two pumps is up to 10% in the worst case. Characterization of the interaction is a laborious work, and it is not expected to significantly improve the design of the system, so it is neglected.

2) Shape of The Force Space: The discrete force space is generated from the combinations of each pump's experimentally determined force space. The combination of 40 values of rpm, 20 nozzle angles and 10 reversing cup positions for the two pumps form 1.44×10^6 solutions. The solution is generated in less than one second from a Python code that runs on a 1.8 GHz Intel PC. The force space is shown in Fig. 6. Pure sway (no surge and yaw) is limited to 110 N, which is very low under the target of 700 N sway force. It was experimentally shown that 110 N is insufficient to beat a lateral current over 0.7 m/s with the current boat. The surge force range is one order of magnitude higher than that of sway, which makes a highly non-uniform force space and a poor omnidirectional maneuverability. Moreover, a particular range of nozzle angle is very sensitive since each degree makes a change of thrust angle of 11 degrees. The reversing cup is obviously not designed for omnidirectional propulsion, and the sway force is very low. Theoretical best reversing cup is calculated to allow 3 times more sway force, but this is still under the targeted value of 700 N.

D. Model Specific to the Multi-jets Concept

Figure 3 shows the propulsion system of the multi-jets concept. The flow in one pipe network is controlled by the restriction from 3 electric valves and by the engine speed.

1) Propulsion Model: The sum of all jets thrust taken at the center-of-mass of the boat is the propulsion forces and moment. The change of momentum from the flow at one jet exit gives the jet's thrust by momentum balance:

$$Thrust = \rho Q^2 / A_{Nozzle} \tag{2}$$

where ρ is water density and A_{Nozzle} is nozzle area.

A hydraulic model of the pipes network is coupled with the experimentally characterized pump to calculate the flow in each of the fix nozzles around the hull by matching the network and pump heads:

$$H_{network}(Q) = H_{Pump}(Q) \tag{3}$$

The pipes network must follow the conditions that each parallel branch has an identical head loss, and each piece of pipe in series have the same total flow :

$$\Delta H_0 = \Delta H_3 + \Delta H_1 (= \Delta H_3 + \Delta H_2) \tag{4}$$

$$\Delta H_1 = \Delta H_2 \tag{5}$$

$$Q_3 = Q_1 + Q_2 \tag{6}$$

$$Q_{total} = Q_0 + Q_1 + Q_2 \tag{7}$$

The total head of the network, $H_{network}$ in Eq. (3), is equal to the head of pipe 0 since pipe 0 is a direct link from the pump to an exit.

A simple and reliable way to calculate viscous flow in ducts [9] is:

$$\Delta H = \frac{Q^2}{2A^2 g} \left(\frac{fL}{d} + \sum K \right) \tag{8}$$

where H is hydraulic head, Q is flow, f is Darcy friction factor, d is pipe diameter, A is pipe area, L is pipe length, and K are loss coefficient to account for elbows, valves and diverse piping elements other than the pipe. Values are taken from fluid mechanics textbook [9].

The loss coefficient for valves is express as a flow coefficient C_v, which is related to the valve percent lift. The relation depends on the valve design.

The ball valve flow coefficient exhibits an equal percent type relation:

$$C_v = (Rn^{(L-1)} + (L-1)/Rn) C_{op.} \tag{9}$$

where $C_{op.}$ is the open valve flow coefficient, L is the percent lift of the valve, R_n is valve rangeability, which is the ratio of the maximum to minimum controllable flow rate.

Gate valve flow coefficient is approximated by surface integral of the open area, scaled to obtain the open valve coefficient in fully open condition. A shift parameter is added to account for the fact that the first percents of lift may create no opening:

$$C_v = (\pi R^2/2 - Y\sqrt{R^2 - Y^2} - R^2 \sin^{-1}(Y/R)) C_{op.} \tag{10}$$

$$Y = (R - 2RL + shift) \tag{11}$$

where R is a radius set to a constant value of $\sqrt{1/\pi}$ to have unit area in fully open condition.

The pump was characterized for engine speeds between idle and 4500 rpm with an experimental setup where an ISA 1932 long radius nozzle flow-meter measured the flow, while a butterfly valve was swept from wide open to fully close. It covered all possible head and flow condition over the range of rpm. A polynomial is least square fitted over the experimental data. The measurements are normally distributed around the interpolation with zero mean and a standard deviation of 4%.

The flows in each pipe, Eq. (4) to (7), is solved with Powell hybrid numerical method, chosen for its fast convergence property [10]. The coupling of flow and head in the pump and in the pipe network at a given engine speed, Eq. (3), is solved with Brent's method [11]. The bracketing feature of this algorithm is needed to bind the flow inside a valid range of the pump polynomial interpolation. The result is the flow in each pipe, and thus the thrusts, for a given rpm and combinations of valve openings. The thrust from each nozzle is transferred from the position of the jet exit to the center of mass. The combinations of all possible valve restrictions and engines' speed generate the force space.

2) Genetic Algorithm Optimization of the Design: The position and angle of each nozzle are optimized to produce the best shape of force space. The cost function used to evaluate the maneuverability quality is based on the projection of the discrete force space on a shell in the shape of the desired force space (Figure 5). The shell is an ellipsoid discretized in small regions by projection of plan grids. The size of the region is such that there is about ten times less region than there are points in the discrete force space. For each force and moment point, a coefficient α is calculated as the proportion between the norm of its position and the norm of its projection on the shell. The weighting of each region is the highest α of all the points projected in that region. Weightings are limited to a value of one since there is no advantage to go beyond the desired force space. The objective function is then the sum of all region's weighting, normalized by the maximum overall weighting.

A genetic algorithm is well suited for bounded non-linear global optimization. The optimization is done with a Galileo implementation from openOPT library [12]. The nozzle positions are bonded to be on the water line of the boat. The angle of the jet is not permitted to have less than 15 degrees with the hull to avoid the need of very elongated hole for the nozzle.

3) Shape of The Force Space: Figure 7 shows the force space resulting from the optimization process. The force is of the same order of magnitude in all direction and reaches the design requirements. Compared to the two-jets concept, the force space is much more uniform and the maneuverability quality is significantly improved.

E. Model Parameter Calibration

Both concepts are inherent to miscalibration, which detracts the system from the expected behavior. Model prediction is improved by calibrating a selected set of parameters. For this, measurements of the force on the boat for a series of maneuvers are made via a truss with load cells. The selected parameters are varied in a modified Powell's

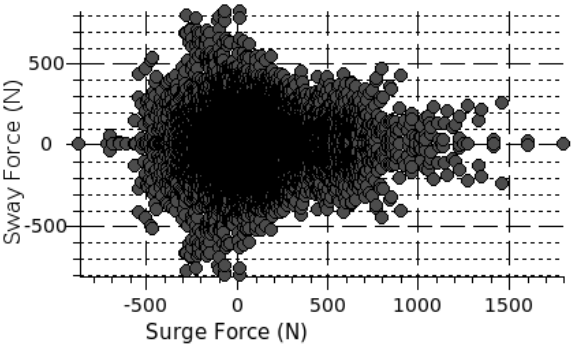

Fig. 7. Slice of optimized discrete force space for the multi-jets concept (between -80 Nm and 80 Nm)

method until the forces predicted by the propulsion model are closest to the measured forces. The criterion to minimize is the sum of Euclidean distance between the predicted and measured force and moment. The moment is scaled to have an equivalent effect as the forces. The data series is a rich set of combinations of forces and moments in all axes, and retains information over the entire force space. The correction parameters are bounded, so the correction does not make major changes. The set of corrected parameters must be small and relevant for the identification to be computed in respectable time.

a) In the two-jets concept: Parameters chosen for calibration are the direction nozzle and reversing cup angles (ϕ, θ, see Fig. 2). Measurement errors of angles for the direction and reversing cup were present in the water-jet characterization and in the final system calibration. These errors, unless corrected, adds-up and can make noticeable deviation from the expected behavior in real trials on a lake.

b) In the multi-jets concept: From various trials, it was found that a good set of parameters for error identification is:

- Ball valve R_n and $C_{op.}$ in Eq. (9)
- Gate valve $shift$ and $C_{op.}$ in Eq. (10)
- Loss coefficient in each of the 4 pipe segments
- Each pump's first order polynomial coefficient

The left and right systems are considered similar, except for the pumps. The position and angle of the nozzles are not a sensitive parameters within the construction precision of the prototype and do not need calibration.

F. The Simulator

The simulator diminishes the need for outdoor trials and offers a total control on the parameters of the boat. It is a consistent platform for clients to assess the maneuverability performance of propulsion systems and controllers. The effects considered are: actuators' dynamic, wind force based on angle dependent drag coefficients [13], current force, and noise level.

The simulator is a 3D game engine with a joystick input that runs the propulsion model of the boat in soft real-time. The motion of the boat from the action of the propulsion forces is calculated by the kinetic model presented below. The simulator is scripted in Python with numpy-scipy modules [14]. The joystick interface and the 3D environment are added around the kinetic model with the Soya3d [15] game engine. Figure 8 shows a typical output of the simulator.

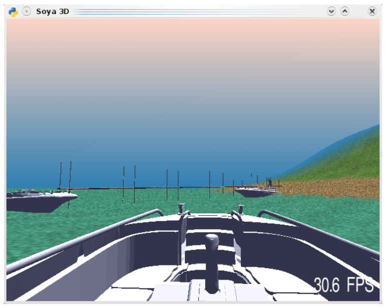

Fig. 8. Snapshot of the simulator window

Kinetic Model: The dynamic of the boat is described by a planar linearly damped rigid body pushed by punctual propulsive forces:

$$M^b_{RB}\dot{v} + D^b v = \tau^b \tag{12}$$

where subscript b is in the boat frame of reference, M_{RB} is rigid body mass matrix, D is damping matrix, v is velocity in the boat frame of reference, and τ is the control forces. A more precise formulation in [16] includes velocity dependent damping, hydraulic added mass matrix, and 6 degrees-of-freedom, but the low velocity considered makes the linear formulation sufficiently accurate for our simulator to represent the performance of the various designs.

Manufacturer data and CAD objects gives the mass matrix M^b_{RB}. Experimental identification of the damping parameters was obtained by recording the boat's response to initial velocity conditions in many different directions. A GPS and accelerometers measured the motion of the boat in free damping. The least square identification with the kinetic model of Eq. (12) gives a rough estimate of the damping matrix.

It is noteworthy that the damping matrix shows cross-coupling between sway and yaw. A yaw moment is created and calls for a velocity dependent compensation to keep the bow from preceding the stern as sway velocity increases.

III. SIMULATION AND EXPERIMENTAL RESULTS

A. Trials on the Lake

Each concept was prototyped and tested on a lake to verify the propulsion model's predicted force and behavior. Trials showed qualitatively similar behavior with the simulator in both cases. The two-jets concept sway force was measured with a hand held dynamo-meter. The force was 70 to 80 N, which is comparable to the predicted 100 N in the test conditions. Similarly, Fig. 9 shows force measurements for the multi-jets concept. Measured sway force agrees quite well with predicted sway force.

The primary criterion of the design is the pilot's feeling of maneuverability. Ten potential clients were asked to pilot the boat and give their appreciation. Clients where mostly unsatisfied with maneuverability of the two-jets concept using original parts, while all were satisfied with maneuverability of the multi-jets concept, with the multiple jets.

1) Errors Identification: For experimental calibration, it is decided to go further only with the multi-jets concept, since it is more promising than the two-jets concept. Figure 9 shows the improvement of the multi-jets concept model after parameters calibration, where the average error is decreased by 60%. The left and right pumps must be considered as different to obtain a good fit with the identification algorithm.

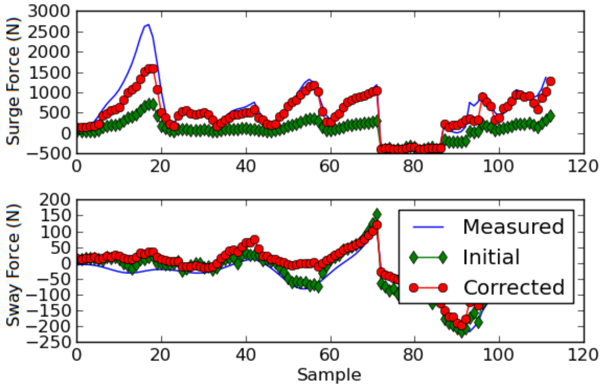

Fig. 9. Calibration of multi-jets model to fit measured forces

2) Closed-loop Control: This section presents the result of a preliminary closed-loop controller with joystick now being a velocity command. Velocity feedback from a noisy GPS and compass is fed to a proportional controller. The measurement noise level is estimated from in-house tests. The open-loop and velocity feedback controllers are compared in the simulator with a human operator accomplishing a predefined square trajectory while keeping a constant heading. A 0.3 m/s south-east current is present. Figure 10 shows the joystick commands invoked by the operator. Both system lead to straigth motions without significant trajectory deviation. As shown in the figure, the velocity controller, although simple, reduces significantly the effort of maneuvering required to maintain trajectory.

A trial with calibration errors is simulated. The open-loop system lost strait motion accuracy. Whatsoever, the velocity feedback largely compensated the errors, and exhibited robustness to miscalibration.

The most important results from this experiment is that the present project offers a propulsion system and a simulation tool that makes controller design an easy and fast work. Besides, it clearly demonstrates that closing the loop is relevant. Simple pilot assistance is evident, but it is also possible to work on features such as dynamic positioning and automatic ship berthing.

IV. CONCLUSIONS AND FUTURE WORKS

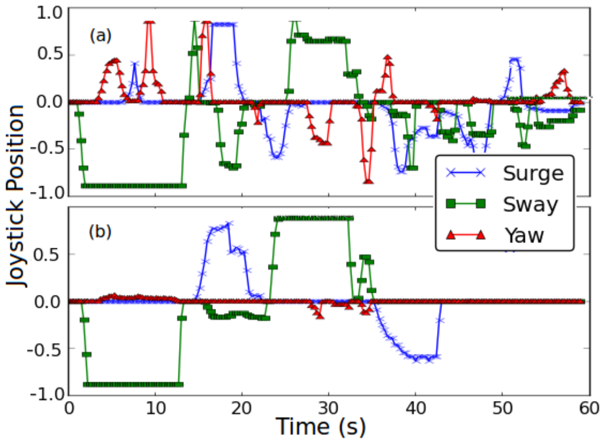

Fig. 10. (a) Open-loop vs. (b) proportional velocity feedback with multi-jets concept

In conclusion, a simulator, backed by experimental results permitted to evaluate and optimize two omnidirectional propulsion systems. The two-jets concept, which is to control the original parts was shown to have too little sway force compared to surge. The multi-jets concept was optimized and its improved omnidirectional force space was shown to have much better maneuverability than the two-jets concept, and to respond well to the design requirements.

The performance of the multi-jets system under open-loop control is acceptable. This mode is essential for a commercial system since it provides a fundamental failsafe mode. Yet, closing the loop and implementation of appropriate control algorithm improves maneuverability and tolerance to variation of system parameters. Some adaptivity could be introduced to correct system changes such as jet-pumps aging. Future work will use the simulator to implement improved control algorithms.

REFERENCES

[1] Side-power bow & stern thrusters (2010). http://www.side-power.com.
[2] Mercury marine. http://www.mercurymarine.com/.
[3] Volvo penta IPS 2007-2008. http://www.volvo.com/volvopenta/na/en-us/.
[4] Bulten, N. W. H., 2006. "Numerical analysis of a waterjet propulsion system". phD, Eindhoven University of Technology.
[5] Seil, G. J., 1997. "Computational fluid dynamics investigation and optimisation of marine waterjet propulsion unit inlet design". phD, University of New South Wales, Dec.
[6] Terwisga, T. J. C., 1996. "Waterjet-Hull interaction". phD, Delft University of Technology.
[7] Bertram, V., 2000. *Practical Ship Hydrodynamics*, 1 ed. Butterworth-Heinemann, Aug.
[8] Cun-Gen, L., Yong-Ming, Q., Zhen-Qiu, Y., and Jie-Ren, L., 2000. "Application of genetic evaluative algorithm in ship preliminary design". *Journal of Shanghai Jiaotong University,* **34**(1), pp. 41–5.
[9] White, F. M., 2003. *Fluid mechanics*, 5th ed. ed. McGraw-Hill, Boston.
[10] Yang, W.-Y., 2005. *Applied Numerical Methods Using MATLAB*. Wiley-Interscience, Hoboken, N.J.
[11] Brent, R. P., 1972. *Algorithms for Minimisation without Derivatives*. Prentice Hall, Oct.
[12] Kroshko, D. L., 2009. OpenOpt. http://openopt.org/Welcome.
[13] Journe, J., and Massie, W., 2001. "Offshore Hydromechanics". Delft University of Technology.
[14] Jones, E., Oliphant, T., Peterson, P., et al., 2001–. SciPy: Open source scientific tools for Python.
[15] Lamy, J. Soya3D. http://home.gna.org/oomadness/en/soya3d/index.
[16] Perez, T., 2005. *Ship motion control: course keeping and roll stabilisation using rudder and fins*. Springer, London.