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New Applications

Small-Scale DP Systems

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Abstract

As DP hardware becomes smaller and less expensive, DP systems will be found on smaller vessels, including unmanned surface vessels (USVs). Some of the key aspects of applying dynamic positioning concepts to small manned boats and USVs are presented, from both a mathematical and a hardware perspective.

Introduction

Most of the world's dynamic positioning (DP) vessels are medium to large sized, and the majority of these support the offshore oil industry. The term *dynamic positioning*, though its meaning has expanded in recent years, has traditionally described the use of a surface vessel's own actuators (propellers, rudders, etc.) to automatically hold a fixed position and heading without the use of mooring or anchoring equipment. In this paper the phrase *DP System* refers collectively to all of the software and hardware components on the vessel used to safely achieve dynamic positioning.

From a mathematical perspective, dynamic positioning is a control systems problem. As such, many of the control algorithms commonly used in the aerospace industry, robotics laboratories, automated manufacturing plants, and elsewhere have also been applied to the dynamic positioning problem, including the well-studied PID, or proportional-integral-derivative, controller.

When reliability is critical, as is the case in the majority of DP applications, another important aspect of a DP system is redundancy. A DP system will often have at least twice the amount of hardware (including actuators) than is strictly necessary to maintain station. A good example of this is a drillship that must maintain a fixed position and heading while drilling (within a certain tolerance) or risk damaging expensive equipment and possibly leaking oil into the ocean (though other safety measures will be in place to prevent leakage). A redundant DP system is designed in such a way that if one device fails, the DP system will bring a backup device online, or use the devices already online, to continue to maintain station within required tolerances.

As DP consoles, computers, I/O cabinets, and sensors continue to shrink (both in size and price), DP systems will be found on smaller and smaller boats. Whereas traditionally the market for DP systems has been driven by the need for vessels to perform industrial tasks quickly and reliably, it is likely that more and more small vessel owners will want smaller, more cost effective DP systems to perform less critical tasks. In these cases redundancy will be less of a concern, and the casual DP consumer will not be burdened by the costs of superfluous computer systems, sensors, actuators and I/O cabinets. Two examples are a small yacht operator that wishes to maintain station away from traffic while waiting for another vessel to vacate his spot at the dock, and a fishing boat operator that wants to conveniently execute a purely sideways ("crabbing") motion while docking.

Aside from this potential "DP for convenience" market, DP-like systems are already finding their way onto small to very small vessels in the form of unmanned surface vessel (USV) control systems. Many USVs are essentially modified versions of Jet Skis, inflatable boats, SeaDoos, and other small manned craft [1]. While most of the current applications for USVs involve moving at transit speeds rather than the low speeds seen in DP applications, is not inconceivable that as DP systems become more available to smaller vessels, more DP applications for USVs will be found.

This paper explores some of the important aspects of applying dynamic positioning concepts to small vessels such as pleasure craft, fishing boats, and USVs.

Time-Scaling Considerations of a Small Vessel

Before a vessel is constructed from a new design, a scaled model is often built, and then tested in an experimental tank (e.g. tow tank, wave basin). Sometimes DP systems are installed on the models to test the holding capabilities of the vessel under various environmental conditions. One important thing to consider when designing and evaluating the DP system on a model vessel is time-scaling. In general, the smaller the DP vessel gets, the higher are the required bandwidths of the various components of the control system. To properly take time and distance into account, a mathematical relationship between the kinematics and dynamics of the model-sized and full-scale vessels must be established. As will be discussed later, lessons learned from scaled models of large vessels can also be applied to small full-scale vessels.

When designing a model-sized vessel, certain requirements can be applied that simplify the analysis:

Simplifying Design Requirements for a Model Vessel

1. The model is geometrically similar to the full-scale vessel, meaning that the geometric proportions of the ship have been preserved.
2. The model has roughly the same average density as the full-scale vessel
3. Any forces applied to the vessel are scaled with the *mass* of the vessel.

Note that this is just one possible set of simplifying requirements. It is reported in [2] that some model designers have considered models that, for example, aren’t geometrically similar. As we will see, Requirement 3 results directly from the first two requirements and our assumption of hydrodynamic similarity between the model vessel and the full-scale vessel. Also, refer to [2] for a more in-depth discussion of model similarity, including skin friction, waves, etc.

In the following analysis, we will use the subscripts *f* and *s* to refer to the full-sized vessel and the scaled model, respectively. For simplicity, but without loss of generality, we assume the vessels are constrained to move in one dimension.

Applying Requirements 1 and 2, it can be shown that the mass, *m*, of each vessel is related through the geometric scale factor λ (where $\lambda > 1$), by:

$$m_f = \lambda^3 m_s. \tag{1}$$

Now we write the net force *F* exerted on the vessel due to waves, wind drag, hydrodynamic drag, and the vessels’ own actuators as:

$$F = F_{wave} + F_{wind} + F_{hydro} + F_{actuator}. \tag{2}$$

Using Requirement 3 and Equation (1), the net force F_f on the full-scale vessel can be written

$$F_f = \lambda^3 F_s. \tag{3}$$

Next we require that the two vessels be *kinematically* similar, meaning that the position, velocity, and acceleration values of the respective vessels can be related through a dimensional transformation. The dimensional transformation can be expressed as:

$$d_f = \lambda d_{s,} \tag{4}$$

$$t_f = \tau t_{s,} \tag{5}$$

where *d* is the dimension of distance, and *t* is the dimension of time. The time-scale factor τ is yet to be determined. Using these transformations, the velocity, v_s, and acceleration, a_s, of the model can be written:

$$a_s = \frac{\tau^2}{\lambda} a_{f,} \tag{6}$$

$$v_s = \frac{\tau}{\lambda} v_{f.} \tag{7}$$

The equations of motion can be written:

$$F_f = m_f a_f, \tag{8}$$

$$F_s = m_s a_s. \tag{9}$$

It then can be shown, using the preceding equations, that

$$\tau = \sqrt{\lambda}. \tag{10}$$

The forces generated by the vessel's own actuators, by wind drag, and by waves can, in theory, be directly controlled by a tank test operator to satisfy Requirement 3. Of particular interest is whether the hydrodynamic drag forces on the vessel satisfy the requirement. Using a standard model of hydrodynamic drag [2], we write

$$F_{hydro} = \frac{1}{2} c\rho v^2 A, \tag{11}$$

where *c* is the coefficient of drag, *ρ* is water density, and *A* is the reference area. From Requirement 1, we know that the reference area of the scaled model can be written:

$$A_s = \frac{A_f}{\lambda^2}. \tag{12}$$

Furthermore, we assume that the model has been designed such that *c* is identical to that of the full-scale vessel. Using the previous equations, it can be shown that

$$\frac{1}{2} c\rho v_s^2 A_s = \frac{1}{2} c\rho v_f^2 A_f \left(\frac{1}{\lambda^3}\right). \tag{13}$$

This equation shows that the hydrodynamic drag force scales with volume, and therefore with mass, satisfying Requirement 3.

In addition to being able to predict the performance of a full-sized vessel based on model data, we can go the other way and use the DP system of a large vessel to design a DP system for a smaller vessel. For example, consider an 80-meter boat that requires a maximum control cycle time of, say, 500 milliseconds, and requires certain minimum actuator, filter, sensor, and controller bandwidths. If we have a 5-meter boat of approximately the same shape and average density, with maximum thrust ratings that are scaled down using the weight ratio of the two vessels, these time-related values can all be scaled using Equation (5). In this case, the maximum control cycle time would be $500\sqrt{\frac{1}{16}}$ = 125 milliseconds.

Hardware Considerations of a Small Vessel

One of the most common sensors found on DP vessels, the mechanical gyroscope, is typically too big and too expensive to be practical on smaller vessels. Fortunately, small heading sensors have recently emerged that perform comparably to gyroscopes and cost significantly less. This includes options such as GPS heading receivers. These heading sensors rely on multiple (usually two or three) GPS receivers to determine the orientation of the vessel in space. The result is one sensor interface that outputs both position and heading data. Figure 1 shows a Trimble position and heading receiver, with two GPS antennas.

Other technologies include fluxgate compasses and magnetometers. A 3-axis magnetometer was successfully implemented for position control in [3]. As the name implies, magnetometers are a kind of compass, in that they that operate using the earth's magnetic field. The price of the magnetometer shown in Figure 1 was recently listed at around $60, which is much lower than other options.

Figure 1. Trimble SPS361/461 unit and antennas, and MicroMag 3-axis magnetometer (right).

While the remainder of the critical DP sensors, such as DPGS units and VRUs, are typically small enough to be less of a concern on all but the smallest vessels, there are other DP components that might normally take up too much space. These include the computers, displays, and consoles (which often include a joystick and optionally a keyboard). L-3 DP&CS has recently combined these three components into a single compact unit, shown in Figure 2. These PRO-Series controllers utilize virtually the same software as their full-sized counterparts from the NMS6000 product line, but are smaller and less expensive.

Figure 2. PRO-Series Controller by L-3 DP&CS.

Actuating a Small Manned Surface Vessel

One barrier that must be overcome before DP systems are commonly found on small, manned vessels is that of poor actuation. Some common DP actuators include main propellers, rudders, tunnel thrusters, and azimuthing thrusters. A well-designed DP system will have one or more actuators located both at the bow and the stern of the vessel. Most small fishing boats, yachts, and speedboats, however, are only equipped with stern actuation, usually in the form of one or more inboard or outboard motors. In the case of inboard motors, a rudder is usually placed behind each propeller to provide yaw (steering) and sway (lateral) actuation.

A vessel that has two inboard propellers (“twin inboards”) and two rudders can be configured to move in a purely sideways fashion. Such a motion can be useful for docking. To achieve this, the pilot “splits” his motors by commanding one ahead and one in reverse. If he wishes to move the boat to port, the port engine should run in reverse. Likewise he should run the starboard engine in reverse if he wishes to move to starboard. The rudder located behind the forward-acting propeller is then deflected outward. An outward deflection is required to counteract the turning force (or “moment”) created by splitting the main propellers. The throttles of the forward and aft thrusting motors are then readjusted as needed to ensure that the vessel moves sideways without rotating, and without sliding forward or backward.

If the vessel is equipped with a “drive-by-wire” rather than cable-driven throttle and steering system, a DP system can be installed that is capable of executing this maneuver with much greater ease and accuracy than is possible with a human operator. Furthermore, the DP system is (theoretically) fully controllable, since the number of independent actuators (one rudder, two propellers) is equal to the number of degrees-of-freedom (surge, sway, and yaw) of the vessel. As a consequence, such a vessel can theoretically maintain a desired position and heading away from the slip, as if anchored, or move slowly along a predetermined track. In practice, a vessel that only has propellers and rudders will constantly have to switch between the “port ahead” and “starboard ahead” split motor configurations. This is not desirable for propellers that, unlike the variable pitch variety (for example), cannot quickly and easily change their direction of thrust.

To aid with getting underway and docking, some boats are equipped with tunnel thrusters at the bow and stern of the vessel. Figure 3 depicts a tunnel thruster installed in the hull of a small boat, as well as an externally mounted thruster. These thrusters exert a force in the lateral direction, and can be used together to create a purely sideways motion. A boat with twin inboard motors and a bow thruster will DP significantly better than a boat that just has twin inboards, and the split motor configuration can remained fixed, saving the motors from having to change direction. In fact, the improvement seen by adding actuation at the bow makes the bow thruster a virtual necessity for a DP boat with propellers and rudders at the stern. Finally, a boat that has twin inboard motors, a stern thruster, and a bow thruster will have significantly reduced rudder and main propeller activity, and improved performance compared to the previously mentioned cases.

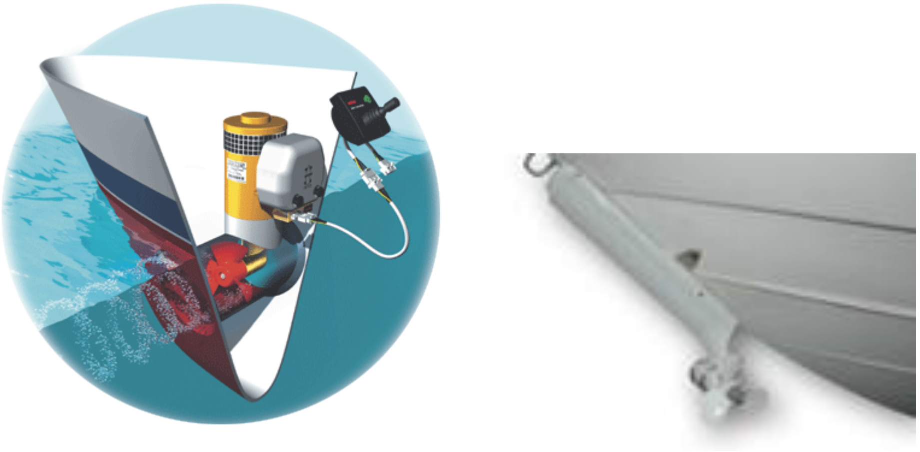

Figure 3. Bow thruster installed internally (left) and externally (right) on a small boat.

Unmanned Surface Vessels

Like their better known aerial counterparts, unmanned surface vessels (USVs) perform a variety of important tasks (see [1] and [4]). Some of these include rescue operations, surveillance, geographical surveying [5], mine hunting, pirate hunting, and warfare. Figure 4 shows a combat USV, and a surveillance/reconnaissance type USV.

Many USVs are essentially modified versions of small manned boats, such a SeaDoos and Jet Skis. Some USVs are semi-submersible, making them nearly invisible above the waterline, except for a protruding snorkel-type device that allows the engines to "breathe". Presently, USVs rely on either remote piloting or an autopilot-based guidance system to go where they are needed. Control of the USVs typically occurs from a host vessel, whose range from the USV depends on the capability of the wireless communications link, and how far the USV can go without refueling.

Figure 4. Surveillance USV, "Interceptor", and Israeli Combat USV, "Protector" (right).

If DP systems become commonly found on USVs, it is possible that more and more USVs will be designed with dynamic positioning in mind (as is the case with supply vessels, for example, in the offshore oil industry). In this case small tunnel thrusters at the bow and stern, as well as one or more main propellers that can change their direction of thrust without de-clutching (e.g. an electrically driven propeller, or a controllable-pitch propeller) would suffice for dynamic positioning.

In addition to autopilot and track-keeping capabilities, a true DP system on a USV would bring with it the capabilities of station-keeping, precise low-speed maneuvering, and relative positioning.

Conclusions

Some of the main issues with placing DP systems on small vessels have been presented. These include: poor actuation, large and expensive sensors and other hardware, and increased control requirements resulting from a faster time scale. As smaller and more cost-effective DP systems prevail, it is the author's view that these issues will be overcome, and small, simple, and non-redundant DP systems will be available to a larger community of users and applications.

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