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USE OF GPS FOR A BERTHING GUIDANCE SYSTEM

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Abstract

The research was conducted in view of automatic berthing of a large merchant ship. This paper discusses the general concept of an automatic berthing system. A GPS-based system, which provides the necessary information on position, velocity, attitude (roll, pitch, and heading), angular velocity and time, will be a principal sensor in a berthing system. The tests were conducted on board a hydrographic sounding ship to obtain the information from a GPS-based system. The data was processed using the software where the algorithms developed in this research are implemented. This paper also discusses various aspects concerning the real-time GPS-based system in relation to an automatic berthing system, such as integration of sensors, port infrastructure, training of crews.

1. INTRODUCTION

Berthing maneuver is the most delicate and difficult but important phase in ship's navigation. It requires many skilled crews, but still depends on the eyes and sensing of a human as it did before. A safe and reliable berthing to the wharf plays a key role to the completion of the mission of sea transportation. The advent of huge vessels and the change to smaller crews on board have made it more difficult and more complicated than ever. The most difficult aspect of berthing maneuver is the manipulation of various actuators, *e.g.*, rudder, propeller, engines. The techniques of this maneuvering are normally acquired by years of experiences. If an operator could carry out the berthing maneuver without any complicated operation, human errors can be eliminated and then safer navigation could eventually be achieved.

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In a man-machine system, such as a ship, a human operator plays an important role for carrying out missions and increasing total system performance. However, the human's performance varies with physical and mental conditions. An operator's workload, biorhythm and autonomic nervous activity are in close relation to his ship maneuvering ability (MURAYAMA *et al.*, 1995; KATO *et al.*, 1996). Abnormal life hours and style due to watch shift and limited onboard neighbors are sources of stress, fatigue and psychological strain which lower the physiological and psychological function of human's body. The time dominates the biorhythm of crews and statistically, accidents are likely to occur midnight to early morning, in particular congested area and narrow channels. Berthing operation imposes a large workload to crews, the errors are more likely to occur by the psychological strain under such condition. Safe navigation will be achieved by lowering a workload of operators with aid of a guidance system and automation.

2. AUTOMATIC BERTHING SYSTEM

In fact, automatic systems are actually increasing the importance in many fields, but automation of ship's navigation is far behind state-of-the-art technology, compared to applications for aircraft and land vehicles. The reason lies in the fact that the detection of position and motion is affected by a surrounding environment which changes every moment. Detection of slower movement is more difficult and the disturbances acting on the ship more largely influence the maneuvers at lower speed. Path planning in harbor is 2-dimensional and user-dependent for ship's berthing, contrary to aircraft landing, which is assisted by the approach lines. Another reason is that ships' crew was used to be large, hence low pressure for automation. However, an autopilot system which allows automatic steering appeared a long time ago. It now equips most ships and is useful for ocean and coastal navigation. Automatic berthing would require an autonomous system.

2.1 Problems of ship's berthing

The development of autonomous controllers of mechanical systems (ships, robots, submersibles, *etc.*) has led to active research in motion planning (DJOUANI and HAMAM, 1995). The problem of ship control involves an optimal and flexible trajectory planning problem and a trajectory tracking problem. The former problem is to find an optimal trajectory to ensure a typical ship maneuver in confined water, under the conditions where a ship, a description of its environment, the differential equations that describe its dynamics, constraints on the steering system, on the ship position, velocity, and acceleration were given. As an example, ship berthing with saving time-fuel objective, is considered. The latter problem is to design a feedback controller which tracks the given accuracy under the conditions where a reference trajectory and a description of a ship as a non-linear dynamic system were given. The problem is very complicated by the nature of the system to be controlled. Controlling a ship at the berthing stage requires precise estimation and prediction of the ship's path. The estimates of state vectors are fed into the controller. However, few systems that could provide necessary information for ship berthing presently exist on board ships. The possibility of precise real-time positioning lies in the utilization of the kinematic technique using carrier phase of GPS (Global Positioning System), which is widely used in the field of surveying. The carrier phase measurement is ambiguous with the number of the cycle integers because GPS receivers can measure only the fractional part of the initial phase. Rapid and reliable resolution of phase ambiguities provide an ultimate accuracy for positioning and attitude determination using GPS. The determination of the ambiguity parameters while remote receiver is moving is called "on-the-fly" (OTF) ambiguity resolution. Recent advances in the OTF technique of phase ambiguity resolution have led to various GPS applications (HATCH, 1990; CHEN, 1993; SANTERRE *et al.*, 1994; TEUNISSEN *et al.*, 1997). However, as GPS is not a perfect system in all circumstances, a single system deficiency may require integration with other systems on board the ship.

3. DEFINITION OF STATES AND DYNAMIC MODEL

3.1 Definition of states

The axes fixed in the ship form a right-hand orthogonal system. The origin, O is at the center of the gravity of the ship for all time, *t*. The x-axis is along the center plane of the ship, coincident with the longitudinal axis of the inertia and its positive direction is forward. The z-axis is also in the center plane of the ship, but normal to the x and is positive downward. The y-axis is normal to x and z and is positive to starboard. The ship dynamic model is assumed to describe a ship as a rigid body with six degrees of freedom. Roll (ϕ), pitch (θ) and yaw (Ψ) are the rotary ship motions about x-, y- and z-axes, respectively (Figure 1). Surge, sway and heave are the translatory ship motions along the same axes (MANDEL, 1967).

3.2 Ship's dynamic model

In order to estimate a ship's path and predict the state for controlling in a berthing operation, one must employ the ship's maneuvering model. The maneuvering model includes numbers of hydrodynamic coefficients. These hydrodynamic coefficients represent the behavior of a particular ship. Every ship has her own set of coefficients. The hydrodynamic coefficients are the principal terms in the mathematical model used in the simulation and prediction of ship maneuvers. The coefficients, which for a given ship, are usually evaluated based on constrained tests of a model in a towing tank, may suffer scale effects when applied to the full-size ship, especially for full forms and in shallow water. Different mathematical models are found in the literature (ABKOWITZ, 1980; TAKAI and OHTSU, 1990; WULDER, 1992; BURNS, 1995). The mathematical model must be physically meaningful and applicable to sea trials, adaptive to wide range of conditions (shallow water, slow speed, confined water, *etc.*) and express the relationship to the real ship. The model varies depending on the types of ship, the use of the model, and the assumptions being made. There exist several models regarded as standard, but the actual model still depends on the user. Mathematical models commonly used include the motion of surge, sway and yaw. KOBAYASHI, (1993) mentions that the necessary information on ship's motion for berthing maneuver includes the yaw/heading angle, yaw rate, position (relative position to the berth), forward and lateral speeds. BURNS (1995) has used a mathematical model in which the motion of roll, pitch, heave are taken into account. The assumption that there is no roll, pitch or heave would not be adequate, for example, the berthing in open port under rough weather.

3.3 Measured states

As the GPS can produce 3-dimensional navigation solution, and as to produce an optimal estimate of the state above and also to be more flexible with different types of ship's models used, the measurement will be made for the 12 variables, *i.e.*, position of the ship's antenna (x, y, z), velocity (u, v, w), roll (ϕ), pitch (θ), yaw/heading (Ψ), roll rate (p), pitch rate (q) and yaw rate (r). Controlling the movement relative to the z-axis is limited for a surface ship. Thus, the final output of the integrated system for a berthing guidance system will be set to the 6 variables (x, y, u, v, Ψ, r) and distance to the berth (D: distance-off). The distances of the fore and of the aft are denoted D_{fore} and D_{aft}, respectively. These D_{fore} and D_{aft} are calculated once the position and heading of the ship with adequate information of the quay, shape and size of the ship are available. The definition of the states to be measured is shown in Figure 1.

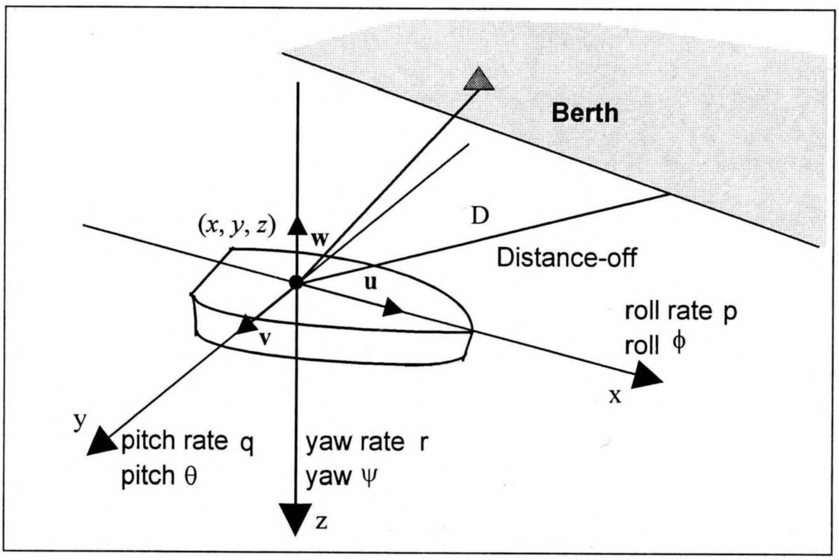

FIG. 1.- Definition of states to be measured.

3.4 Criteria of sensors

The requirements for navigation systems in general concern the following points: capability (accuracy), availability, continuity, reliability and integrity (VIEWEG, 1993). Different types of system parameters are described and used in the Federal Radionavigation Plan (FRP, 1997). When the navigation solution is discussed, the problems are their accuracy and reliability.

Criteria of sensor requirements for ship's berthing are defined in the following. Any captain knows the approximate position and speed of the ship without the help of a positioning system in a berthing operation (UENO and HAYASHI, 1992). The level of 2D-positioning accuracy that the captain has, is comparable to that of landing aircraft, *i.e.*, ±0.6 m (vertical, 2σ) and the detectable speed at the final berthing stages is as low as 5 cm/s. At the final stage of berthing procedures, before touching the quay, the maximum speed of approach to the berth is limited by the attitude of ship, characteristics of fenders, *etc.* The speed of approach depends on the size of the ship. In general, such speed must be less than 10 cm/s, for large ships, whose size is over 5 000 t or over 100 m in length. In fact, the speed must be 2-5 cm/s, and excessive speed may cause damage to the hull and quay structures. The minimum performance required to the velocity is that the speed of the final approach, *i.e.*, 2 cm/s, is detectable. The level of accuracy which can calculate the D_{fore} and D_{aft} with precision of ±0.6 m (2σ), will require at least ±0.05° for a ship of 300 m. TAKAI and OHTSU (1990) mention that automatic berthing requires very accurate information on yaw rate, and they used a rate integrating gyro for measurement and as backup of gyrocompass in their berthing experiment. Thus, one requires, for the turn rate (yaw rate), a resolution of ±0.01°/s and accuracy of ±0.02°/s, *i.e.*, as accurate as a rate integrating gyro or equivalent. Required reliability of the navigation solution is close to 100%. The criteria of sensor requirements are summarized in Table 1.

Table 1.Sensor requirements for the berthing of a 300-m ship

	Position	Velocity	Heading	Yaw Rate
Accuracy	±0.3 m	±0.02 m/s	±0.05°	±0.02°/s
Reliability	~100 %	~100 %	~100 %	~100 %

4. GPS-BASED SYSTEM FOR A BERTHING SYSTEM

4.1 GPS-based positioning and attitude system

The main component on board the ship is the GPS-based system consisting of (3 or) 4 GPS antennas and receivers. The data from one of these onboard receivers are also used for determination of the ship's position and velocity. The measurements from the onboard sensors are time tagged or synchronized using an external clock and stored in a buffer or temporary memory. When the estimation of clock parameter becomes unnecessary, *e.g.*, in such a case that GPS antennas are connected to a single receiver, sensitivity and number of unknowns to be estimated are reduced (COHEN, 1992; UENO *et al.*, 1997). The data are called by interrupt control and processed in the main computer. The fifth (or fourth) receiver is at the GPS reference station and the measurements, *i.e.*, the carrier phases, pseudoranges and Doppler are received through a radio link. All measurements at the reference station must be transferred. Other sensors, necessary to acquire enough information to reliably resolve integer ambiguities for attitude determination could be an inexpensive roll and pitch sensor and gyrocompass or magnetic compass.

The GPS user has to keep in mind that the position of antenna is determined. If it is necessary to obtain the motion of another point of the ship, like the center of gravity, the antenna position has to be transformed to the desired point. The measurement model of the ship's position measured by a GPS receiver is obtained after the transformation. The measurement model is used when the ship's position is calculated before getting into the Kalman filter for the estimation of the state vector and computation of control input. If the GPS data is used in another mode such as raw data, the signal model will change accordingly.

4.2 Real-Time kinematic GPS

In connection with relative GPS positioning and velocity determination, the shore-based reference station has the same number of observables as for the ship station. For real-time applications, the reference station must have a radio link to transfer the data to the ship using a local telemetry unit (RTCM, 1994). When the number of observables is increased at the reference station as well as the ship station, the message length of the measurement data becomes longer, and as a result, it takes longer time to transfer the data to the ship station.

Real-time implies that the transfer of data must be at a very high Baud rate. SCHWARZ *et al.* (1994) conducted tests of time latency of radio link by sending C/A-code, L1 phase and D1 Doppler measurements with 9 600 Baud rate. For 7 satellites, the time latency was about 1.4 second. At the present date, higher Baud rate is available. When the Baud rate of 57 600 is used, the time latency would be diminished to 0.3 second. The impact of time latency would be less critical for ship's berthing applications, where the ship's speed is low. Since controlling a ship is based on the predicted state estimate, the time latency would not be a deterministic factor for the implementation of berthing system, although a good prediction model of filtering would be required.

Code correction and correction rate are currently broadcasted in marine DGPS network. If carrier phase correction and correction rate are available in marine DGPS network, it would be advantageous to real-time applications in terms of computation and time latency. However, even if the phase correction and correction rate were broadcasted, the closest GPS reference station available for a ship in particular port could be about a hundred kilometers away. If it is as far as 200 km, the effect of prediction errors would not be negligible, due to loss of precision when the distance from the reference station increases. Other error sources such as modelling of atmospheric errors would also affect the precision of relative positioning. Thus, a GPS reference station should be set up in port.

Figure 2 shows the flowchart of the real-time integrated system. Two computers will be used on board a ship. One would be allocated for processing GPS data and the other for processing the data from other sensors, *e.g.*, ship's speed log, gyrocompass, and for backup. In the host computers, the software will perform the following tasks: i) read data from the serial ports by the use of interrupt control, ii) search ambiguity and produce a first result of position, velocity, attitude and attitude rate by combining carrier phase, pseudorange and Doppler data and useful information from other sensors or characteristics of ship maneuvering, iii) integrate other measurements and hydrodynamic model using an extended Kalman filter to produce optimal estimate and control at the epoch or to prepare a backup system for the case of complete loss of solution from GPS-based system due to loss of track of satellites, iv) monitor the status of the GPS system or other sensor systems and v) if the GPS system does not provide data, allow other systems to back up or make a prediction by a Kalman filter.

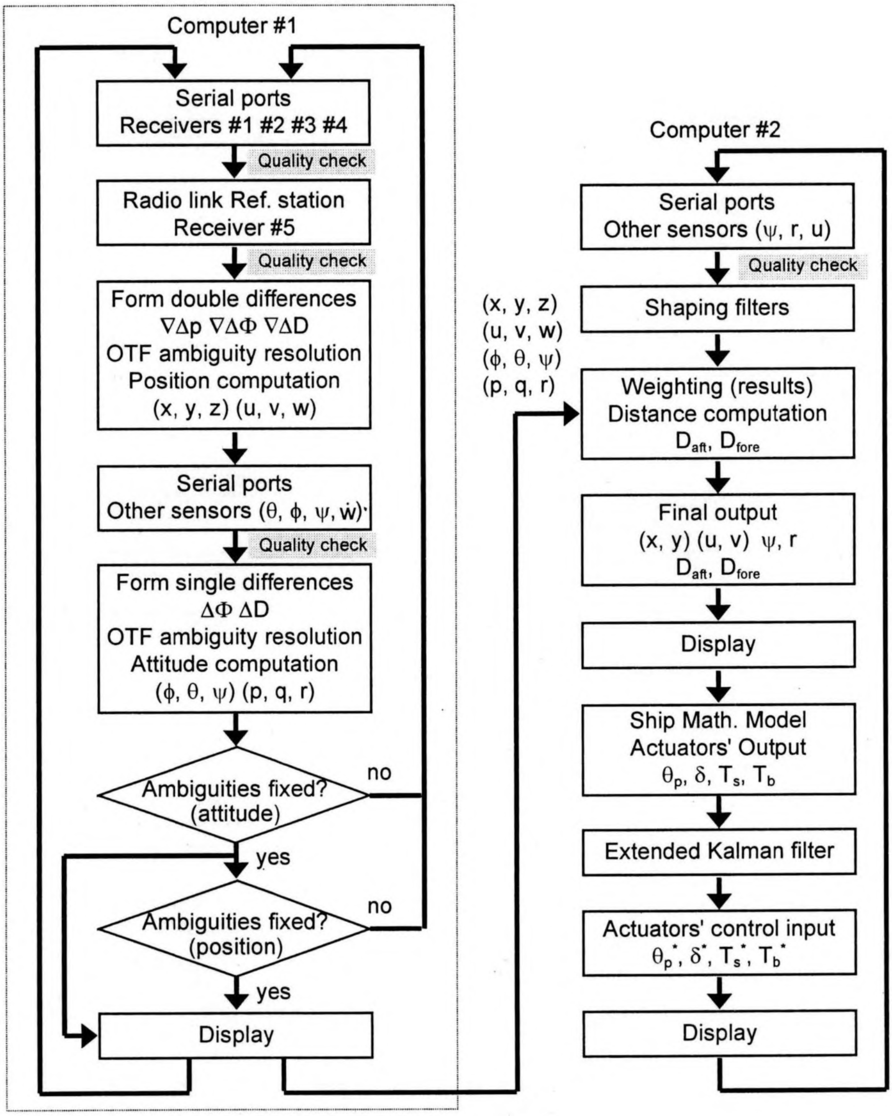

FIG. 2.- Flowchart of the real-time integrated system.

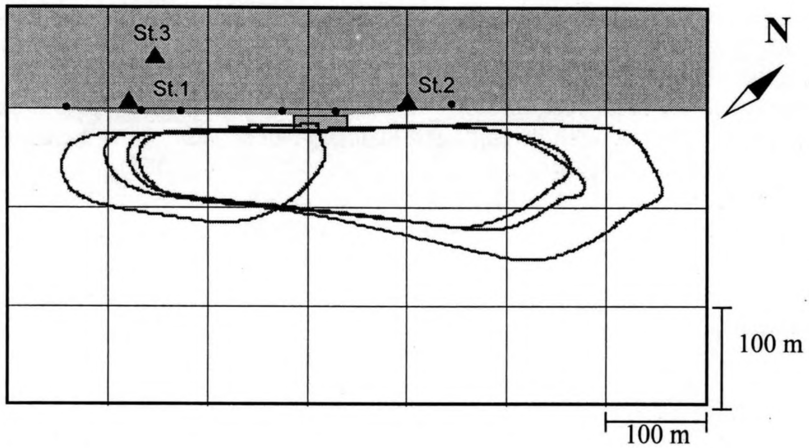

FIG. 3-. Trajectory of Smith during the test.

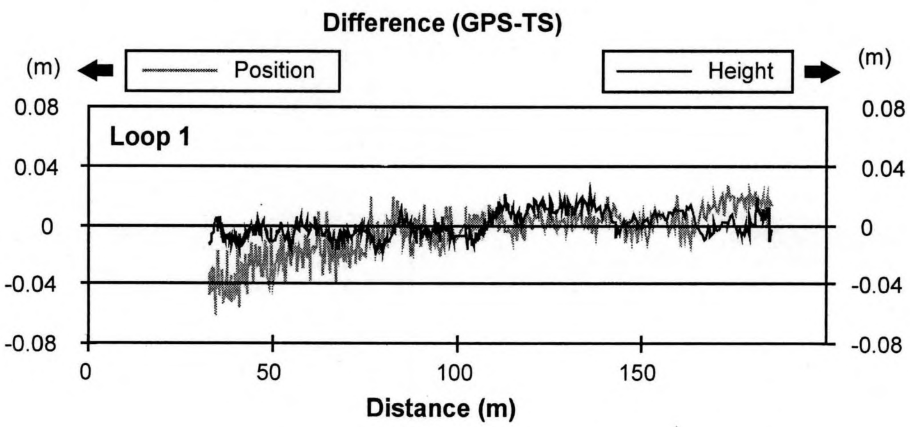

FIG. 4-. Difference in position between GPS and total station (Loop 1).

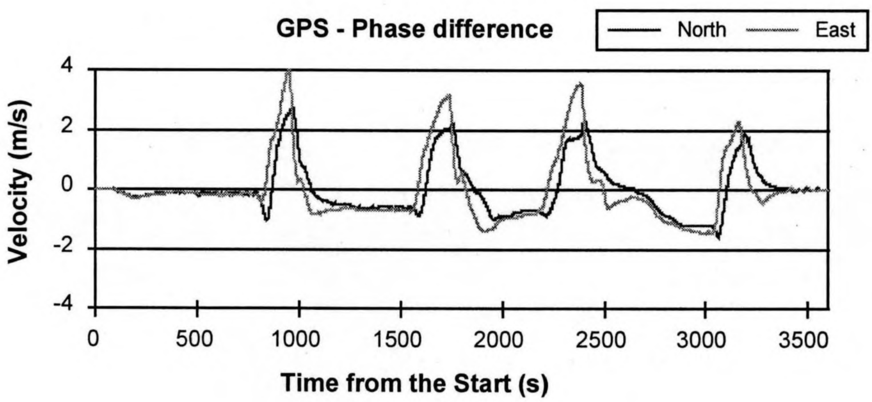

FIG. 5-. Velocity determination using GPS phase difference.

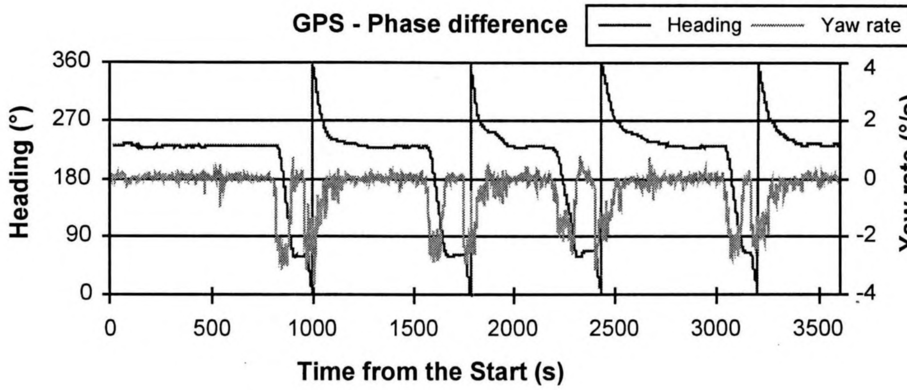

FIG. 6-. GPS heading and yaw rate determination.

A test on board a hydrographic sounding ship, "F.C.G. SMITH", was conducted at Trois-Rivières, *ca.* 130 km upstream of St. Lawrence River, southwest of Quebec City, on 17 November 1997. SMITH with a stable catamaran platform was considered suitable for simulating a behavior and the characteristics of a large ship. The objectives of tests are to verify the performance of the algorithms and the quality of navigation solution (which corresponds to the part with computer #1). The data was post-processed using the software where algorithms developed in this research was implemented (UENO, 1998; UENO and SANTERRE, 1998a, 1998b). Figure 3 shows the results of GPS positioning using OTF technique. During the approach to the wharf, the ship was tracked using a total station with an automatic tracking function (typical precision under favorable condition: ±5 mm). Figure 4 shows the difference of position between the GPS and total station. The difference was about ±2 cm for horizontal position and ±1 cm for height. Figure 5 shows the results of the ship's velocity calculation using temporal difference of phase observations. Figure 6 shows ship's heading and yaw rate obtained from our GPS-based system, consisting of an optimal configuration of 4 antennas. The results showed that the accuracy of kinematic GPS positioning is better than ±5 cm, and that accuracy of attitude is better than ±0.5° with an antenna separation *ca.* 1.4 m compared to the results of external sensors (TSS and gyrocompass). The precision of velocity using temporal difference of phase measurements is *ca.* ±2 cm/s and that of yaw rate with 1.4-m antenna separation is about ±0.2°/s.

4.3 Integration of sensors

GPS positioning in kinematic mode implies lower degrees of freedom than static positioning, because of the number of unknowns to be resolved, compared to the number of observation at every epoch. Therefore, redundant measurements would be required. As GPS is not a perfect system in all circumstances, a single system deficiency may require integration with other systems on board the ship. A preliminary choice of sensors to be integrated can be made on the following basis: i) systems that already exist on board normal ships could be used, ii) too many additional systems should not be installed for the purpose of berthing, and iii) expensive systems are not desired.

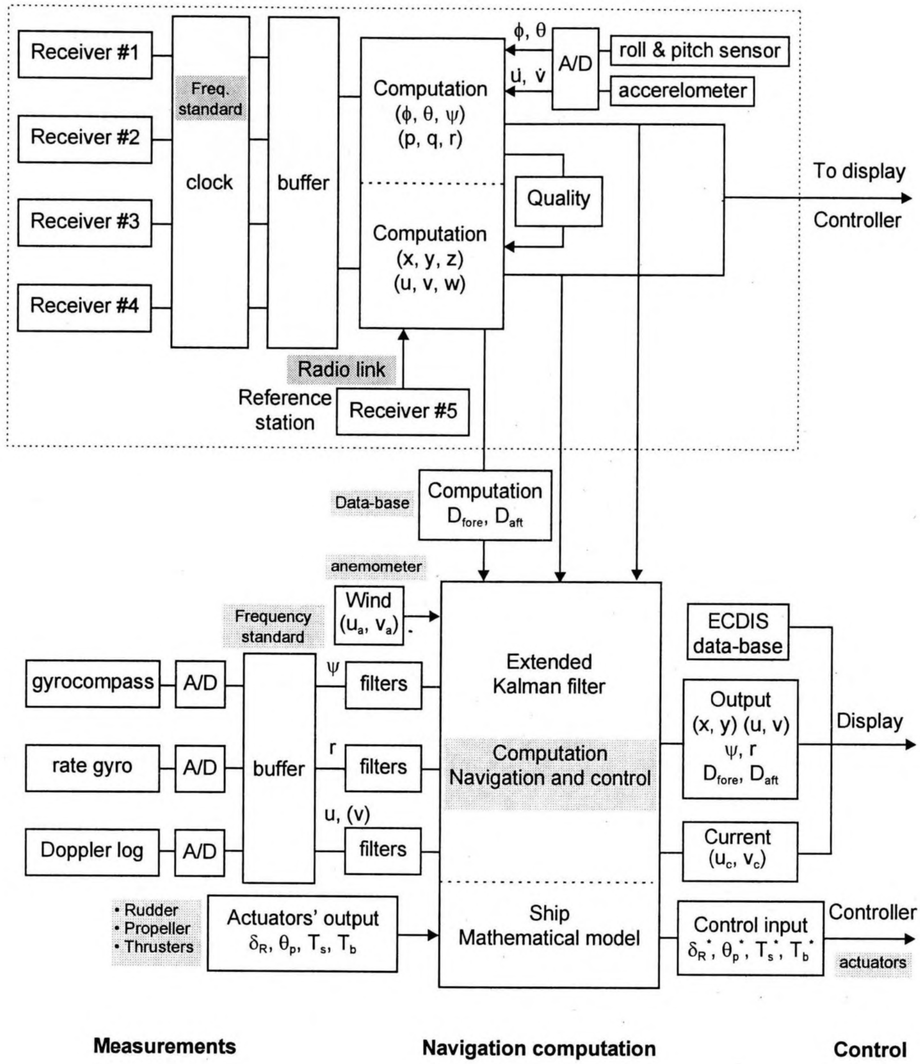

FIG. 7.- Configuration of the real-time integrated system

In the area of aviation, GPS/INS integration is common practice. However, the INSs for ships are expensive because the voyage lasts much longer than aircraft. Thus, much more precise INSs are required and they must regularly be updated by GPS or other methods. As a result, normal ships are not equipped with such systems. It follows that the other systems with the GPS-based system will be gyrocompass, rate integrating gyro, Doppler sonar log as in the example of the use (TAKAI and OHTSU, 1990). The information from measurements with a log is useful to estimate the current velocity. Analog data measurements, if there are, of the sensors would be digitized through the A/D converting interfaces with the time of measurement. Data intake can be sequential, but a precise clock for sensor timing from GPS or an external clock will be required. These measurements, through shaping filters to eliminate the noise could be integrated to the GPS measurements in order to give better estimates, or be used to form a backup system in case that the GPS system is not available.

In order to control a ship at the time of berthing, special measurements related to actuators' status are required. The measurements are the torque of the propeller shaft, the number of revolutions, the rudder angles and the velocity and direction of wind. Simple instruments could provide sufficiently accurate measurements for these measurements. The instruments are, for example, strain gauges for the torque of the propeller shaft, pulse counter for the engine revolution, a potentiometer for the rudder angle, wind vane or anemometer for wind. The systems which facilitate berthing maneuver are thrusters and controllable pitch propeller (CPP).

The dynamics of the sensors are important for the integrated navigation system. The measurement model, the knowledge of the statistics of the measurements and the system noise for each sensor will be required for the integration.

A tentative system configuration is shown in Figure 7. The variables concerning actuators in Figure 7 are summarized: δ_R is rudder angle, θ_p is the blade angle of a controllable pitch propeller, T_s is the thrust of stern thruster and T_b is the trust of bow thruster. The variables with asterisks are the ordered values for the actuators. The variables, u_c and v_c are the longitudinal and lateral components of current velocity and u_a and v_a show the same components but for wind velocity.

4.4 Extended Kalman filter

Accurate estimation and prediction of the ship's position and vector (*i.e.*, forward and lateral speeds, heading) are required in order to provide correct commands for control. A Kalman filter would be employed in order to integrate the measured data from various sensors of different accuracy and to give an optimal estimation of position, velocity, yaw/heading and yaw rate (state vectors).

Controlling a ship is done at the predicted position based on the estimates obtained from the various sensors. Implementation of a Kalman filter is ideal to integrate the all time-stamped data, including GPS-based system. Use of a Kalman filter combined with a ship's model could be suitable for the estimation of values without measurements. An extended Kalman filter could be used to estimate those unknown parameters of ships which contain hydrodynamic coefficients together with state vectors (MILLER and DOVE, 1991). However, implementation of the mathematical model requires intensive labor and computation time to solve a number of hydrodynamic coefficients. The model must be precise to reconstruct the estimates without measurements but simple enough for the computation. The duration how long the prediction could be accurate enough for controlling a ship depends on the accuracy of the maneuvering model.

An extended Kalman filter could be used to estimate the current velocity using the GPS velocity determination and speed log measurements. If thrusters are not available, another model with the use of tugboats must be developed. However, an autonomous system without a tugboat is easier for development of an automatic system. As a feedback of the state vector is used in the control routine, a simplified model can be used. The calculation of control input could be simpler with the employment of a state feedback. Some examples of the use of mathematical model are in (TAKAI and OHTSU, 1990; WULDER, 1992; BURNS, 1995).

4.5 Integrity of system

When the overall system becomes complex, the possibility of a failure increases. If the system become unable to produce the required estimate, the operator must immediately be informed. "Integrity" is the ability of a system to provide timely warnings to users when the system should not be used for navigation (FRP, 1997). In other words, a navigation system having sufficient integrity will inform to the operator, when it is presenting erroneous data beyond the limits for proper navigation (KINAL, 1991).

The extreme reliability required for precision approach establishes the need for an active integrity verification system, in aircraft applications. A GPS receiver must be able to detect and reject satellite signals that would lead to unacceptably large position and velocity errors. A number of useful RAIM (Receiver Autonomous Integrity Monitoring) and RAIM-type algorithms have been developed to detect and isolate the failed satellite for civil aviation (KOVACH *et al.* 1994; KINAL, 1991).

RAIM type integrity monitoring scheme would be required for berthing operation. Using the RAIM scheme, the quality of measurements could be monitored, and unfavorable data could be eliminated for further computation. The quality of real-time carrier phase correction and correction rate could be monitored on board a ship. For kinematic GPS, using the flags which show the status of ambiguity resolution and square-root of the *a posteriori* variance factor, quality of measurement could be controlled. As the GLONASS system is slowly getting to full operation, the use of GLONASS satellites could improve the detection and isolation of erroneous satellite's data.

In ports, it is most likely that the signals of GPS will interrupted by port facilities or derricks of other ships or even by the own structure of the ship. Even in cases of GPS signal loss, it is important to reconstruct the states which are not measured and to resolve GPS ambiguity with the fastest possible computation when the signals are regained. If the system can no longer produce the estimates, the system must have an alarm function.

4.6 Port design for automatic berthing system

Berthing of a large merchant ship sometimes requires tugboats and assistance from shore. After the completion of safe berthing to the wharf, on merchant ships, charge or discharge of cargo immediately starts. The berthing of the ship is the end of sea transportation and a port is the starting point for land transportation. Ports must be convenient for storage and the equipment must be efficient for cargo handling.

Implementation of an automatic system must work for safety of navigation. In this research, fast and reliable ambiguity resolution has been studied but existing ambiguity resolution techniques are all based on the statistics and there is sometimes an exception which does not fit the statistics. In order to avoid such a case, redundant measurements might be a solution. Considering loss of resources and environmental damage due to accidents, and to support the instantaneous and reliable resolution of GPS phase ambiguities for precise kinematic positioning, another measurement such as distance to the berth (with precision *ca.* ±10 cm), an integrity pseudolite beacon, might be needed for the realization of an automatic berthing system. In some ports, there already exists the visual display of distance (microwave or laser measurement) and this kind of support is useful for Masters.

4.7 Training of crews

Use of automated system is increasing in various fields including aviation. However, aircraft's cockpit is filled with different types of displays of machines and sensors. Accidents might occur with a combination of several factors. These factors could be in relationship between a human operator, the machines used in the operation and the operational environment around the human operator and the machines, which provides condition and limitation. A survey showed that up to 80% of airplane accidents were due to the human errors and that the most stressful situation with an automatic system is the situation which requires technical assistance has arrived (BARAYAN, 1991; SARTER, 1996).

Automatic systems must be reliable and the operator must immediately be informed when the failure has occurred. Introduction of automatic system for ships should not be just to fill up the bridge with displays of machines and control panels. Automation of operation should not produce another complexity or danger than improve the operational environment. It is estimated that up to 80% of maritime accidents may be also caused by human errors, such as errors in judgment, communication, measurement, action, *etc.* (MARITIME SECURITY BUREAU, 1995). Less tiring, fool-proof display, user friendly operation and countermeasures for faulty operation are necessary but training of crews is more important. The simulation training for collision avoidance in congested waters is effective. Automation of ships operation needs adequate training for operators when the system is either operational or not. Education for seafarers must include basic art of navigation for the situation that all the navigation systems become unusable.

Technological development influences and sometimes yields a large impact on safety of navigation. If an operator could carry out the berthing maneuver without any complicated operation through automation, human errors can be eliminated and then eventually safer navigation could be achieved.

CONCLUSIONS

Up to 80% of maritime accidents are attributed to human errors. To reduce the workload of human operator and eliminate the human errors, automation of ship's operation would be required.

Controlling a ship in berthing operation requires precise estimate of the state, *i.e.*, position, velocity, heading and yaw rate. A GPS-based system with OTF approach can provide sufficient accuracy for berthing operation. A GPS-based system has a potential to be used as a principal sensor for automatic berthing. However, in order to cover up the single system deficiencies, an integrated system would be required.

A sea port must be designed for supporting the automatic berthing operations. In order to support the instantaneous and reliable resolution of GPS phase ambiguities for precise kinematic positioning, a system which provides the distance to the wharf with a precision about 10 cm, would be required. The system must transfer the data to ship using radio link at very high Baud rate. A GPS reference station must be installed at each port.

When the overall system becomes complex, the possibility of a failure increases. If the system become unable to produce the required estimate, the operator must immediately be informed. Therefore, an adequate integrity monitoring would be required.

Less tiring, fool-proof display, user friendly operation and countermeasures for fault operation are necessary but training of crews is more important. Automation of ships operation needs adequate training for operators when the system is either operational or not. Education for seafarers must include basic art of navigation in case that navigation systems become unusable.

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