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Navigation System of an Unmanned Boat for Autonomous Analyses of Water Quality

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***Abstract*—This paper presents a navigation system for autonomous analyses of water quality using unmanned boats at drinking water reservoirs such as dams and holding ponds. As it is well-known, water quality plays an important role in controlling health and the state of disease. Therefore, it needs to be analyzed at periodical intervals. Various systems exist for automatic analyses of water quality and the common problem of these systems is the complexity associated with collecting samples. To deal with this problem, an autonomous boat loaded with a Sonde with probes can be used for analyzing the quality of water. In this study, the navigation system of the autonomous boat is investigated in detail. In order to prove the effectiveness of the proposed system, MATLAB-based simulation studies were conducted. The results of these simulation studies show that the proposed system can navigate an unmanned boat successfully at drinking water reservoirs. Field tests with an autonomous boat are in progress.**

***Index Terms*—Autonomous analyses of water quality, navigation system, inertial navigation, GPS.**

I. INTRODUCTION

Sustainable use of drinking water resources requires monitoring programs, management tools and decision making tools. In Europe, the Water Framework Directive (WFD) sets the guidelines which define the categories of water quality and the required parameters and components [1]. WFD, US EPA [2] and Turkish Regulations [3] state that dissolved oxygen (DO), electrical conductivity (EC), pH, temperature, nitrate and turbidity are the base parameters for water quality. Collecting water samples is a common requirement of all water quality monitoring systems. Fixed water quality analyzing systems provide accurate and timely water quality data at the expense of high initial investment and maintenance costs. Portable devices used for water quality analyses require the use of utility personnel to perform measurements and do not provide timely data. Since they offer low initial investment costs and significant drop in periodical maintenance costs, these devices are being used widely.

Multi-probe sondes with sensors for measuring various water quality parameters have attracted the attention of researchers around the world. In a research at Nam Co Lake in China, probes with sensors for EC, luminescent dissolved oxygen (LDO), pH and temperature were used [4]. Another research with a probe with sensors for DO measurements was conducted at Toenepi Stream in New Zealand [5]. In addition to various water quality parameters, nutrient quality and bacterial populations in tile drainage and shallow ground water were examined in [6].

Automatic monitoring stations play an important role in controlling water quality and are in use worldwide. These stations involve several components such as sensors, communication technologies, monitoring software and computing technologies. Timely information from water quality monitoring networks characterizes water quality and helps in managing drinking water resources. Practical implementations of these stations were investigated in detail in [7].

Similar to several other applications, unmanned vehicles can also be used for environmental monitoring applications. The use of an autonomous underwater vehicle (AUV) for environmental monitoring is discussed in [8]. In [9], water quality mapping using an unmanned boat is proposed. For this kind of applications, an important criterion is the locations of sampling points [10]. The boat was used at shallow mire pools and was controlled by an operator. The drawback of this research lies in the fact that it was conducted during daylight hours since the boat was ridden by an operator. In fact, DO and pH levels change during daylight hours due to photosynthesis.

Different from the studies in the literature, in this study we propose an autonomous water quality analyzing system using a mini boat. This portable autonomous system can be used at night and reduces initial investment and periodical maintenance costs. Water quality data can be downloaded whenever the boat is in the coverage area of the RF system.

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The remainder of this paper is organized as follows. Section II introduces the use of autonomous mini boats to analyze water quality. Section III introduces the proposed navigation system which is based on the loose integration of INS and GPS data. Simulation studies of the proposed navigation system are given in Section IV. Finally, the paper is concluded in Section V.

II. The Use of an Unmanned Boat for Water Quality Analyses

In this study, the boat is not guided by an operator. As shown in Fig. 1, the boat visits water sampling points by following a predetermined trajectory set by the operator to collect water samples and the probes loaded on the boat measure water quality during these visits. The probes take a large number of samples, measure them and record the results during the mission.

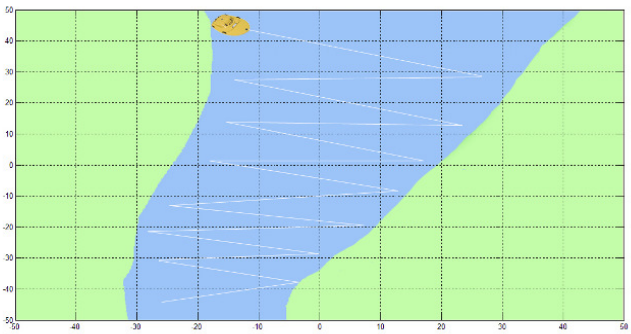

Fig. 1. An illustration of the proposed system.

When the boat has completed its mission, it returns at the shore and the analyses are made after the data have been downloaded. Table I lists the parameters which will be measured by the sensors in this study and their legal limits.

TABLE I. WATER QUALITY PARAMETERS AND LEGAL LIMITS.

Parameter	Limit
EC	2.5 mS/cm according to WFD
DO	5 mg/L according to WFD and 8 mg/L according to Turkish Regulations
pH	6.5-8.5 units according to both WFD and Turkish Regulations
Temperature	25°C according to Turkish Regulations
Nitrate	50 mg/L according to WFD, 10 mg/L according to EPA and 20 mg/L according to Turkish Regulations
Turbidity	Not defined

III. Proposed Navigation System

An accurate model of the autonomous boat is necessary to develop a navigation system [11], [12]. The boat is modelled as a rigid body with six degrees of freedom (DOF) corresponding to translations along the three axes and its rotations about these axes as shown in Fig. 2. Two reference frames, inertial reference frame and body reference frame, are required to obtain the model. Inertial reference frame is fixed to the Earth and its origin is located on the mean water surface at an appropriate location on the boat. Body reference frame is fixed to the hull. To simplify the design, we neglected the centre of gravity by setting the centre line of the boat to the origin [13]. The position and heading of the boat can be described as follows

$$\vec{p} = \begin{pmatrix} x \\ y \\ \theta \end{pmatrix}. \tag{1}$$

Considering the implementation areas of the prototype system which are drinking reservoirs such as holding ponds and dams, the effects of hydrodynamic forces, lifting forces and damping forces are neglected to simplify the design and left as future work. Due to the limited communication distance of remote control systems, autonomous mode is preferred in this study. To enable the boat follow a predetermined trajectory to collect water samples, an INS-based GPS-aided navigation system, shown in Fig. 3, was designed. Considering the limitations of the prototype system and our simulation environment, the loose integration approach is used for the integration of GPS measurements and INS data. In this system, the integrated Inertial Measurement Unit (IMU) provides the reference trajectory and the GPS receiver acts as the updating system due to its limited measurement frequency. The World Geodetic System 1984 (WGS84) is used for the geodetic reference and Earth-centred Earth-fixed (ECEF) is the Cartesian coordinate frame of reference used in GPS.

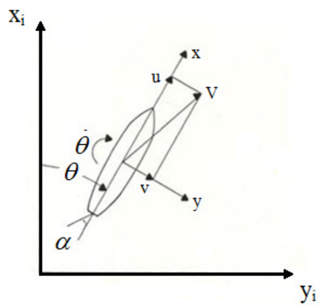

Fig. 2. Boat motion description.

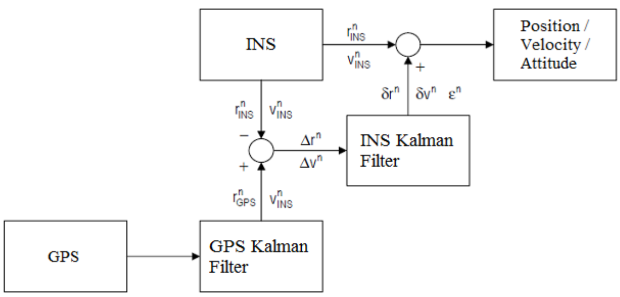

Fig. 3. INS-based GPS-aided navigation system – loose integration approach.

In the proposed boat navigation system, the GPS filter is used for the GPS measurements and the INS filter is used for the INS measurements. This system operates even if one of the INS or the GPS receiver fails [14] and the processing time of this approach is generally less than tight integration-based approaches [15]. The basics of this approach which was adopted from [14] are as follows:

1. By using the mechanization equations, raw INS measurements are processed in order to determine the

position and velocity provided by the INS;

2. In order to determine the position and velocity provided by the GPS receiver, raw GPS measurements are processed through the GPS Kalman filter;
3. The INS Kalman filter determines the error estimates of the position and velocity in addition to misalignment errors by taking the difference between the position and velocity from the first step and second step;
4. Finally, the position and velocity obtained from the first step is updated in order to get the full state vector by using the error estimates obtained in the third step.

The GPS filter uses a position-velocity model to estimate position and velocity errors and its inputs are single differenced GPS observables. The system model includes navigation error states and sensor error states. The following equation can be used to represent the navigation error state vector

$$x_n = [\delta r_x \ \delta r_y \ \delta r_z \ \delta v_x \ \delta v_y \ \delta v_z]^T, \tag{2}$$

where the subscripts represent directions. δr and δv represent the position error vector and the velocity error state vector, respectively. The corresponding position and velocity error dynamic models are:

$$\delta\dot{r} = \delta v, \tag{3}$$

$$\delta\dot{v} = \eta_v, \tag{4}$$

where η_v is the process driving white noise with spectral density q_v. The sensor error state vector is

$$x_s = [ct \ \ c\delta t]^T, \tag{5}$$

where c represents the speed of light, t represents the clock offset error state and δt is the clock drift error state. The dynamic models for clock offset error and clock drift error are:

$$c\dot{t} = c\delta t + cn_t, \tag{6}$$

$$c\delta\dot{t} = cn_{\delta t}, \tag{7}$$

where n_t represents the clock error driving noise with spectral density q_t and $n_{\delta t}$ represents the clock drift error driving noise with spectral density $q_{\delta t}$. Then, the system model can be written in state-space form:

$$\begin{bmatrix} \delta\dot{r} \\ \delta\dot{v} \\ \dot{t} \\ \delta\dot{t} \end{bmatrix} = \begin{bmatrix} 0_{3\text{x}3} & I_{3\text{x}3} & 0 & 0 \\ 0_{3\text{x}3} & 0_{3\text{x}3} & 0 & 0 \\ 0_{1\text{x}3} & 0_{1\text{x}3} & 0 & 1 \\ 0_{1\text{x}3} & 0_{1\text{x}3} & 0 & 0 \end{bmatrix} \begin{bmatrix} \delta r \\ \delta v \\ t \\ \delta t \end{bmatrix} + \begin{bmatrix} 0_{3\text{x}3} & 0 & 0 \\ I_{3\text{x}3} & 0 & 0 \\ 0_{1\text{x}3} & c & 0 \\ 0_{1\text{x}3} & 0 & c \end{bmatrix} \begin{bmatrix} n_v \\ n_t \\ n_{\delta t} \\ \delta t \end{bmatrix}. \tag{8}$$

The process noise spectral density matrix is

$$Q(t) = \begin{bmatrix} q_v & 0 & 0 \\ 0_{1\text{x}3} & q_t & 0 \\ 0_{1\text{x}3} & 0 & q_{\delta t} \end{bmatrix}. \tag{9}$$

The measured pseudoranges and Doppler observables are related to the user's position and velocity through the relations:

$$H(\rho) = \begin{bmatrix} \frac{\partial\rho^1}{\partial r_x} & \frac{\partial\rho^1}{\partial r_y} & \frac{\partial\rho^1}{\partial r_z} & 0 & 0 & 0 & 1 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{\partial\rho^N}{\partial r_x} & \frac{\partial\rho^N}{\partial r_y} & \frac{\partial\rho^N}{\partial r_z} & 0 & 0 & 0 & 1 & 0 \end{bmatrix}_{m_1\text{x}8}, \tag{10}$$

$$H(\dot{\rho}) = \begin{bmatrix} \frac{\partial\dot{\rho}^1}{\partial r_x} & \frac{\partial\dot{\rho}^1}{\partial r_y} & \frac{\partial\dot{\rho}^1}{\partial r_z} & \frac{\partial\dot{\rho}^1}{\partial v_x} & \frac{\partial\dot{\rho}^1}{\partial v_y} & \frac{\partial\dot{\rho}^1}{\partial v_z} & 0 & 1 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{\partial\dot{\rho}^N}{\partial r_x} & \frac{\partial\dot{\rho}^N}{\partial r_y} & \frac{\partial\dot{\rho}^N}{\partial r_z} & \frac{\partial\dot{\rho}^N}{\partial v_x} & \frac{\partial\dot{\rho}^N}{\partial v_x} & \frac{\partial\dot{\rho}^N}{\partial v_z} & 0 & 1 \end{bmatrix}_{m_2\text{x}8}. \tag{11}$$

Measurements are weighted based on the satellite elevation angle e. To predict the measurement errors, the standard deviation of the measurement errors at the zenith is computed and scaled by $1/\sin(e)$ as proposed in [15].

The INS filter provides an estimate of the errors in the INS output. Because of the errors in the measurements, the system state vector is augmented by the sensor error states. By the perturbation of the mechanization equations, the inertial navigation error state behaviour can be described. The model of navigation error states can be described as:

$$\delta\dot{r} = \delta v, \tag{12}$$

$$\delta\dot{v} = N\delta r - 2\Omega\delta v - F\varepsilon + R\delta f, \tag{13}$$

$$\dot{\varepsilon} = -\Omega\varepsilon + R\delta w, \tag{14}$$

where δr, δv, δf, δw represent the position error vector, the velocity error state vector, the accelerometer sensor errors, the gyro sensor errors, respectively. F represents the skew symmetric matrix of forces, ε represents the misalignment error state vector, Ω represents the skew symmetric matrix of the Earth rotation rate relative to inertial space, N represents the tensor of the gravitational gradients and R represents the rotation matrix.

If sensor turn-on biases, scale factor errors and nonorthogonality errors are neglected, the inertial sensor measurement equation can be described as:

$$\delta f = \delta b_a + \eta_a, \tag{15}$$

$$\delta w = \delta b_g + \eta_g. \tag{16}$$

The bias drift δb_i can be modelled as:

$$\delta\dot{b}_a = -\frac{1}{\tau_a}\delta b_a + \eta_{ba}, \tag{17}$$

$$\delta\dot{b}_g = -\frac{1}{\tau_g}\delta b_g + \eta_{bg}, \tag{18}$$

where τ_i is the correlation time and η_{bi} is the Gauss-Markov process driving noise with spectral density q_{bi}.

The process model can be written in state-space form:

$$\begin{bmatrix} \delta\dot{r} \\ \delta\dot{v} \\ \dot{\varepsilon} \\ \delta\dot{b}_a \\ \delta\dot{b}_g \end{bmatrix} = \begin{bmatrix} 0_{3x3} & I_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} \\ N_{3x3} & -2(\Omega)_{3x3} & -F_{3x3} & R_{3x3} & 0_{3x3} \\ 0_{3x3} & 0_{3x3} & -(\Omega)_{3x3} & 0_{3x3} & R_{3x3} \\ 0_{3x3} & 0_{3x3} & 0_{3x3} & (-1/\tau_a)_{3x3} & 0_{3x3} \\ 0_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} & (-1/\tau_g)_{3x3} \end{bmatrix} \begin{bmatrix} \delta r \\ \delta v \\ \varepsilon \\ \delta b_a \\ \delta b_g \end{bmatrix} + \\ + \begin{bmatrix} 0_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} \\ R_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} \\ 0_{3x3} & R_{3x3} & 0_{3x3} & 0_{3x3} \\ 0_{3x3} & 0_{3x3} & I_{3x3} & 0_{3x3} \\ 0_{3x3} & 0_{3x3} & 0_{3x3} & I_{3x3} \end{bmatrix} \begin{bmatrix} n_a \\ n_g \\ n_{ba} \\ n_{bg} \end{bmatrix}. \quad (19)$$

The process noise spectral density matrix is:

$$Q(t) = \begin{bmatrix} (q_a)_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} \\ 0_{3x3} & (q_g)_{3x3} & 0_{3x3} & 0_{3x3} \\ 0_{3x3} & 0_{3x3} & (q_{ba})_{3x3} & 0_{3x3} \\ 0_{1x3} & 0_{3x3} & 0_{3x3} & (q_{bg})_{3x3} \end{bmatrix}. \quad (20)$$

For the loose integration of the two filters, the INS Kalman filter uses the difference between the GPS-derived velocity and position estimates, and the INS mechanization derived velocities and position measurements to obtain the error estimates [14], [16]. The position and velocity covariance matrix is transferred from the GPS Kalman Filter to the INS Kalman filter in order to form the measurement noise for the INS Kalman filter.

IV. Simulation Studies

We developed a MATLAB-based simulation environment to analyze the effectiveness of the proposed navigation system. The simulation environment integrates INS data and GPS data in post-mission mode. Both observation data composed of raw code, phase and Doppler measurements and navigation data composed of ephemeris parameters provided by the GPS receiver are binary files and Receiver Independent Exchange Format (RINEX) version 2.10 files. IMU data are as binary files and text files. After importing previously collected RINEX files into MATLAB and editing them, we simulated the scenario shown in Fig. 4. Figure 5 shows the trajectory errors of the boat from the North and the East. Trajectory errors of the boat are around 0.5 m and these results prove that the proposed navigation system is successful.

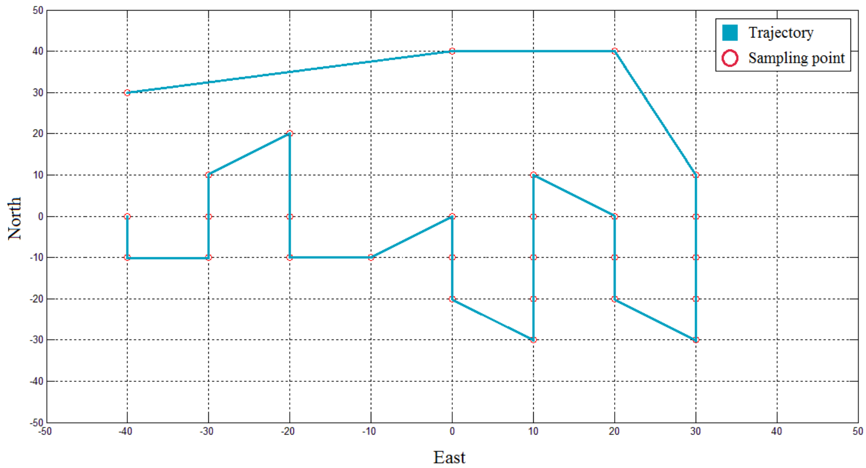

Fig. 4. Actual trajectory of the simulated boat.

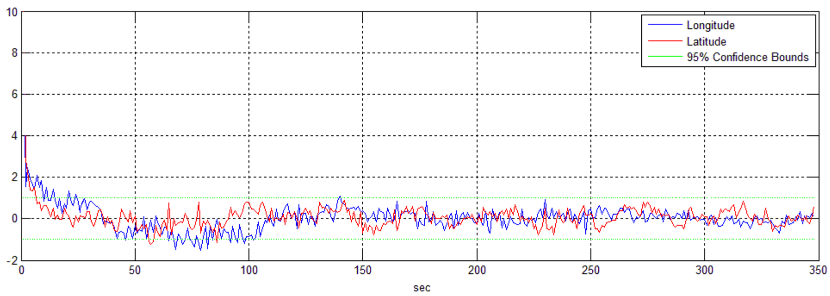

Fig. 5. Trajectory errors of the simulated boat from the East and the North (in meters).

V. CONCLUSIONS

This paper focuses on the navigation system of an unmanned mini boat loaded with multiple probes for autonomous analyzes of water quality at drinking water reservoirs. This portable system brings cost advantages to utility providers by eliminating laboratory expenses and helps in improving the quality of supplied water.

The navigation system is based on an inertial navigation system-aided by a GPS receiver. The results of the MATLAB-based simulation studies prove that the proposed system can navigate an unmanned boat successfully. The proposed low-cost navigation system is suitable for systems with limited processing and memory resources and operates even if one of its sensors fails.

Field tests with an autonomous boat are going on at a drinking water reservoir, Kirklareli Dam, in Turkey. We are currently implementing the proposed navigation system on the prototype boat. After successful implementation of the system, several water quality parameters including EC, DO, Temperature, pH, Nitrate, and Turbidity will be collected and analyzed by the boat.

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