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FUSION OF DATA FROM GPS RECEIVERS BASED ON A MULTI-SENSOR KALMAN FILTER

Summary. In the age of continually developing satellite navigation practically every ship is equipped with GPS receivers, providing the coordinates of her position. However, relying solely on the navigational data from one autonomous receiver the navigator may expect that a given position is burdened with significant errors or that the position data will be lost. This results from the shortcoming of GPS systems which are susceptible to disturbances affecting their operation. One method to substantially reduce such risk is a navigational system that makes use of a number of sources for accurate position determination. The obtained data are processed, which involves data integration and filtration in order to further diminish measurement errors. One possible solution is the application of a system based on an algorithm of multi-sensor navigational data fusion using a Kalman filter. After a brief description of the algorithm, this article presents some results of the fusion of data from parallel position measurements, where the data come from two mobile GPS receivers. The said solution is intended to be implemented in a navigational decision support system on board a sea-going vessel.

FUZJA DANYCH POCHODZĄCYCH Z ODBIORNIKÓW GPS OPARTA NA WIELOSENSOROWYM FILTRZE KALMANA

Steszczenie. W dobie rozwoju nawigacji satelitarnej praktycznie każdy statek jest wyposażony w odbiorniki systemu GPS, wskazujące współrzędne pozycji obiektu. Jednakże opierając się tylko i wyłącznie na informacji nawigacyjnej otrzymywanej z pojedynczego, autonomicznego odbiornika narażamy się na ryzyko wystąpienia znacznych błędów lub utraty informacji pozycyjnej. Wynika to z wady tych systemów, jaką jest możliwość stosunkowo łatwego zakłócania ich pracy. Jednym ze sposobów na znaczne zredukowanie tego ryzyka jest zastosowanie systemu nawigacyjnego, w którym dla dokładnego wyznaczenia pozycji wykorzystuje się dane uzyskiwane z wielu źródeł oraz poddaje się je obróbce: integracji i filtracji w celu dalszego ograniczenia błędów pomiarowych. Jednym z możliwych rozwiązań jest zastosowanie systemu działającego w oparciu o algorytm wielosensorowej fuzji danych nawigacyjnych z wykorzystaniem filtru Kalmana. W artykule, po krótkim opisie algorytmu, przedstawiono przykładowe wyniki badań polegających na fuzji równoległych pomiarów pozycji, pochodzących z dwóch różnych, ruchomych odbiorników GPS. Powyższe rozwiązanie planuje się zastosować w nawigacyjnym systemie wspomagania decyzji na statku morskim.

1. INTRODUCTION

The major principle in good seamanship is to conduct safe navigation, i.e. to steer the ship safely ,in a collision avoiding manner from the point of departure to the point of destination. The problem comes down to finding solutions to two tasks: position determination and plotting the right course to be followed by the controlled ship.

The end of the 20th century witnessed dynamic development of satellite positioning systems. In the age of satellite navigation practically every ship is equipped with a GPS receiver, indicating position coordinates and calculating the covered track. However, if we rely exclusively on navigational information from single, autonomous receivers, there is a risk that major errors or loss of data may occur. This is due to shortcomings these systems have, such as relatively likely disturbance of their operation.

One method to substantially reduce that risk is the application of a positioning system that uses several independent sources of data on the position of a controlled object. Such systems, although constantly improved, indicate a position with a specific accuracy, that is burdened with an error. Aiming at an exact position determination, we can reduce the error by using a navigational system which receives data form a number of sources, and processes these data by their integration and filtration to further reduce measurement errors.

The main advantages of a positioning system that uses the filtration and integration of data from a number of sources are as follows:

- increased reliability of operation,
- reduced measurement errors,
- ensured non-stop operation,
- more frequent data reception.

One possible solution is a system which works is based on an algorithm of multi-sensor data fusion using a Kalman filter, described in Chapter 2 [2]. The algorithm was verified by its implementation as an application working in real time. Chapter 3 presents the results of experimental research, where parallel position measurements were integrated, with data obtained from two mobile GPS receivers.

The above solution is intended to be implemented in a shipboard decision support system [5]. The devised data fusion algorithm may also find applications in the integration of other navigational data from devices and systems installed on a sea-going ship.

2. DESCRIPTION OF THE ALGORITHM

Let us consider a discrete stochastic system with a few sensors:

$$\begin{aligned} \mathbf{x}(t+1) &= \mathbf{\Phi} \cdot \mathbf{x}(t) + \mathbf{w}(t) \\ \mathbf{y}_i(t) &= \mathbf{H}_i \cdot \mathbf{x}(t) + \mathbf{v}_i(t) \qquad i = 1, 2, \dots l \end{aligned} \tag{1}$$

where:

$\mathbf{x}(t) \in R^n$ - state vector,

$\mathbf{y}_i(t) \in R^{m_i}$ - measurement vector of i-th sensor ($1 \le m_i \le n$),

$\mathbf{\Phi}, \mathbf{H}_i$ - constant matrices of proper dimensions,

$\mathbf{w}(t), \mathbf{v}_i(t)$ - disturbance vectors with a characteristic of white Gaussian noise with expected zero values and covariance matrices $\mathbf{Q}$ and $\mathbf{R}_i$, respectively.

The fusion of data set l of sensors is expressed by the weighted mean [6]:

$$\tilde{\mathbf{x}}(t) = \mathbf{A}_1(t)\cdot\hat{\mathbf{x}}_1(t) + \mathbf{A}_2(t)\cdot\hat{\mathbf{x}}_2(t) + \ldots + \mathbf{A}_l(t)\cdot\hat{\mathbf{x}}_l(t) \tag{2}$$

where:

$\mathbf{A}_i(t)$ - weight matrices,

$\tilde{\mathbf{x}}(t)$ - state estimates fusion vector,

$\hat{\mathbf{x}}_i(t)$ - estimates of the state vector.

The estimates of state vector $\hat{\mathbf{x}}_i(t)$ for *i*-th subsystem (defined by a given sensor) are obtained by using the Kalman filter [1,4]. Weight matrices are determined from this formula [7,8]:

$$\mathbf{A}_i(t) = \left[\sum_{j=1}^{l}\mathbf{P}_{jj}^{-1}(t)\right]^{-1}\cdot\mathbf{P}_{ii}^{-1}(t) \tag{3}$$

where:

$\mathbf{P}_{ij}(t)$ - matrix of the cross-covariance of filtration errors between *i*-th and *j*-th subsystem of the system described by the equation (1).

Matrices of the cross-covariance of filtration errors are determined from the formula [7,8]:

$$\mathbf{P}_{ij}(t) = \left[\mathbf{I}_n - \mathbf{K}_i(t)\cdot\mathbf{H}_i\right]\cdot\left[\mathbf{\Phi}\cdot\mathbf{P}_{ij}(t-1)\cdot\mathbf{\Phi}^T + \mathbf{Q}\right]\cdot\left[\mathbf{I}_n - \mathbf{K}_j(t)\cdot\mathbf{H}_j\right]^T \tag{4}$$

where:

$\mathbf{I}_n$ - $n\times n$ unit matrix,

$\mathbf{K}_i(t)$ - filter gain matrix at instant *t*.

Defined by the equations (2), (3), (4) the algorithm is optimal as it minimizes the trace of fusion estimate error variance matrix [7,8].

The following measuring devices seem to be important from the viewpoint of the integration of navigational data available on board ship:

- gyrocompass, used to obtain gyrocompass course measurements, GPS receivers, providing Cartesian coordinates of ship's position,
- Doppler speed log, which measures the longitudinal and transverse velocities of the ship relative to the bottom.

Standard deviations of errors for each measurement device are defined as a half of the error at 95% confidence level, provided by the manufacturer.

In order to make a fusion of measurement data obtained by GPS receivers one has to bring them down to one location on board the ship (location of the most accurate GPS receiver; further in this article GPS1 is assumed to be such receiver) using the measurements of gyrocompass course:

$$\begin{aligned} \breve{x} &= \breve{x} + w_x\cos(\psi) - w_y\sin(\psi) \\ \breve{y} &= \breve{y} + w_y\cos(\psi) + w_x\sin(\psi) \end{aligned} \tag{5}$$

where:

$(\breve{x},\breve{y})$ - measurements of Cartesian coordinates (x, y) of ship's position,

$\mathbf{w} = \left[w_x , w_y \right]$ - vector determining the location of one GPS relative to another (Fig.1),

ψ - gyrocompass course.

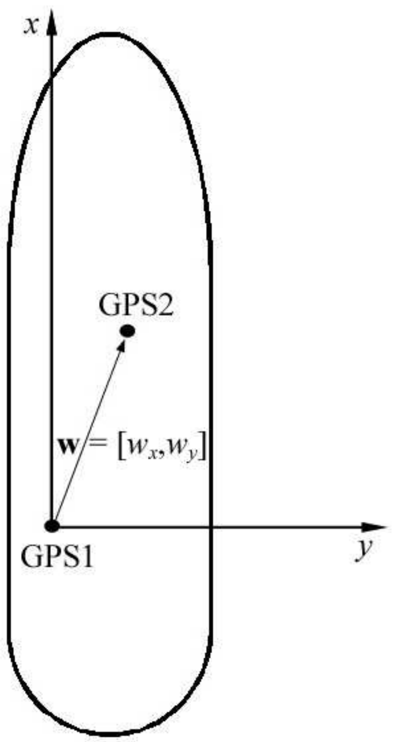

Fig. 1. The vector defining the position of one GPS receiver relative to another
Rys. 1. Wektor określający pozycję danego odbiornika GPS w stosunku do innego

Shifting the GPS measurements will be resulting in an increased error of the GPS receiver by the value:

$$2\sqrt{w_x^{\,2} + w_y^{\,2}} \cdot \sin\left({e_{gyro}}/{2} \right) \tag{6}$$

where:

e_{gyro} - gyrocompass error.

3. RESEARCH

The navigational data fusion algorithm was verified by its implementation as an application working online, i.e. in real time.

The experimental research consisted in the integration, or fusion, of parallel position measurements carried out by two mobile GPS receivers, Holux M-1000 (Fig.2). The geographical coordinates were transformed into Cartesian coordinates [3].

Fig. 2. GPS receivers, Holux M-1000
Rys. 2. Odbiorniki GPS, Holux M-1000

The measurements were repeated a few times along the same straight line section of the ship's track. Each time the vessel was moving between the fixed extreme points at a speed of $1{,}5\ [m/s]$. The receivers mounted on the vessel were placed one metre from each other ($\mathbf{w} = [0,1]$). Figures 3, 4 and 5 present the results of of a number of experiments. One will note that as a result of the fusion the trajectories identifying vessel's position (GPS1) are closer to a straight line, which should be the case. In the initial measurement phase, the data fusion results show a worse quality of estimation, the effect of filter tuning.

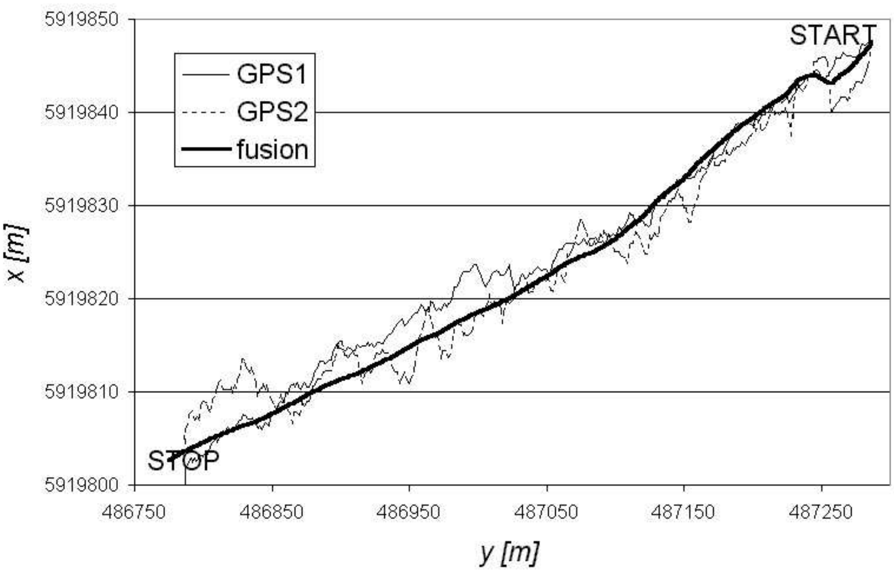

Fig. 3. Positions of a vessel in motion along a straight line section recorded by two GPS receivers and their on line fusion – experiment 1
Rys. 3. Pozycje statku w ruchu wzdłuż odcinka linii prostej rejestrowane przez dwa odbiorniki GPS i ich synteza on-line – eksperyment 1

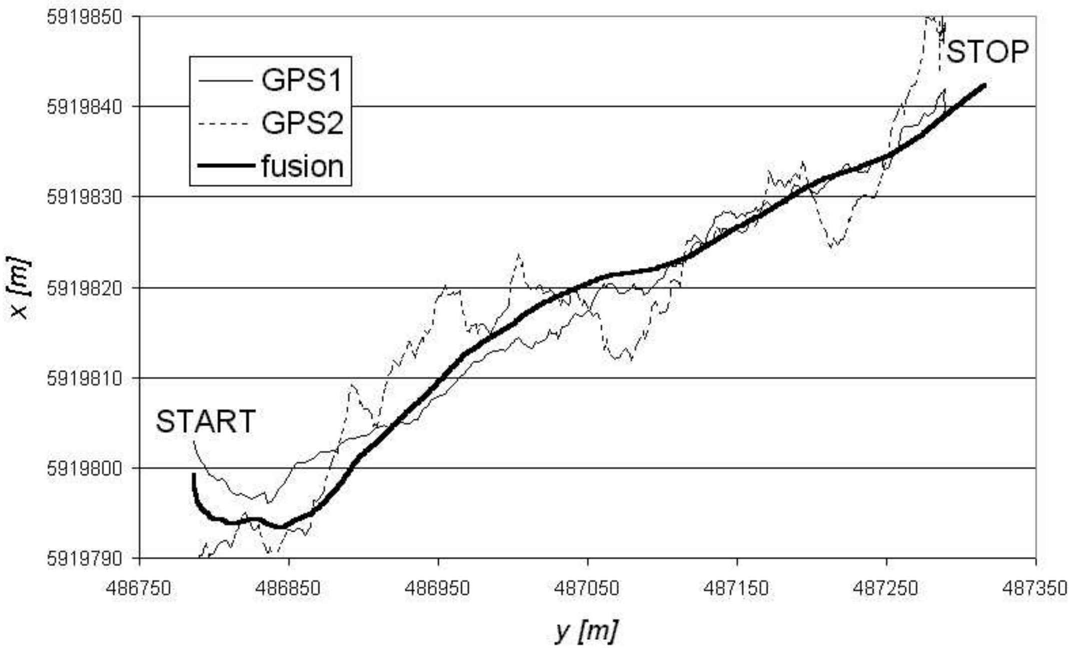

Fig. 4. Positions of a vessel in motion along a straight line section recorded by two GPS receivers and their on line fusion – experiment 2
Rys. 4. Pozycje statku w ruchu wzdłuż odcinka linii prostej rejestrowane przez dwa odbiorniki GPS i ich synteza on-line – eksperyment 2

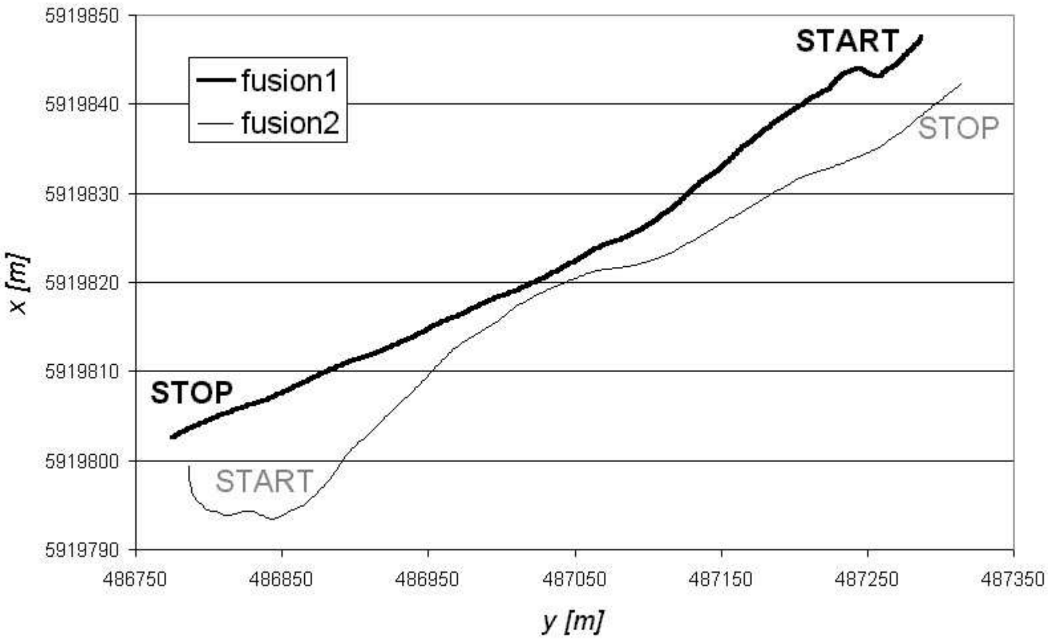

Fig. 5. Trajectories of vessel's movement in experiments 1 and 2 defined in the data fusion process
Rys. 5. Trajektorie ruchu statku w eksperymentach 1 i 2 określone w procesie syntezy danych

Figure 5 comprises the fusion data of vessel's position from the two above mentioned experiments. One can see that in the central part (when filters are already tuned in) both trajectories are close to each other.

4. SUMMARY

The research results confirm the effectiveness of the algorithm of navigational data integration described herein.

The proposed method of data integration and filtration enables combining data from a few autonomous measurement devices into one single signal and the reduction of controlled vessel's position measurement error. The method also ensures better reliability of the system by the acquisition of data from a number of many sensors, which in turn allows to eliminate wrong input data caused by, e.g., measurement system failure.

The performed experiments confirm that the algorithm is a useful tool for the sea-going vessel navigational decision support system.

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