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Development of low cost on-board velocity and position measurement system for wheelchair sports

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Abstract

There has been an increase in popularity of wheelchair sports. It is necessary to develop mobile on-board systems to do measurements in field. This paper presents a low cost on-board velocity and position measurement system for field environments. In the system, two MEMS gyroscopes and two GPS receivers are fixed on the rear wheels’ axles. A Kalman filter is used to integrate position data with velocity data to produce accurate velocity and displacement estimations. The wheelchair’s kinematics can be identified by using the estimations. All of the measurement data are transferred to a computer via a wireless network.

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Keywords: Wheelchair sports; On-board instrumentation; Mobile measurement

1. Introduction

In the last twenty years there has been an increase in the popularity of wheelchair sports [1]. As with all sports, the desire to improve performance is one of the primary concerns of coaches and competitors [2]. A number of off-board wheelchair sports monitoring systems have already been developed [3]. The popular approach used in these systems is to put the monitoring system on a static wheelchair ergometer which is a machine used to simulate the action of propelling a wheelchair for the purpose of training. Much research has been carried out in an attempt to correlate ergometer data and identify information relevant to making a real wheelchair ‘go-faster’. However there are vital differences between performing practice drills on a static ergometer and playing on a court. The best ergometer for athletes is one which closely matches their training or competition.

It is necessary to develop mobile technologies and on-board systems which allow measurements in the field. A recent and increasingly analytical approach is to install the monitoring system on the wheelchair. Some on-board wheelchair monitoring devices, which claim to measure virtually every aspect of a wheelchair athlete’s technique,
have been developed and are available in the current market place [4]. However, current devices are relatively expensive, heavy and to some extent affecting the athletes’ performance [5].

The rapid development of integrated circuit and micro-electro-mechanical systems (MEMS) technology has accelerated research and application of inertial sensors. The MEMS inertial sensors, including gyroscopes have many advantages in size, weight, integration, cost, power consumption and some additional features. But the MEMS inertial sensor is prone to significant instrument biases and drifts due to the noise, device instability and operational environments. For a long period of operation, the MEMS inertial sensor accuracy can be greatly degraded due to its drifting problem.

For wheelchair sports, the capability to provide reliable and accurate position is required and sometimes as well as the capability of continuous positioning and high updating rate. Global Positioning System (GPS) has become a widely used technique for positioning and tracking. However, signal jamming, obstruction, interference and the relatively low update rate are still the major limitations of the low-cost GPS receivers.

In order to improve the performance of measurements and increase the update rate of the positioning system, this paper deals with algorithmic developments of GPS and inertial sensor integrated measurement system. On one hand, the inertial sensor is a self-contained, high update rate device, which does not suffer the signal propagation problems, such as the multipath effects and obstructions, and can produce more continuous positioning estimations. The integration of GPS and inertial sensor system, to some extent, can overcome the problems caused by GPS outage and the update rate can be significantly increased by using the low-cost, high update rate inertial sensor. On the other hand, the GPS positioning method is drift-free, so it can be used as the reference in the inertial sensor error models to deal with the drifting problem. An Extended Kalman Filter (EKF) based algorithm is developed to integrate these two systems.

| Nomenclature |
|---------------|
| \( r \) radius of wheel |
| \( L \) length between two wheel-axles |
| \( w_{\text{left}} \) rotational speed of left wheel |
| \( w_{\text{right}} \) rotational speed of right wheel |
| \( \omega \) turning angular speed of wheelchair |
| \( \theta \) deflection angle of wheelchair |
| \( v_{\text{left}} \) linear speed of left wheel-axle |
| \( v_{\text{right}} \) linear speed of right wheel-axle |
| \( v_{\text{mid}} \) linear speed of middle point between two wheel-axles |
| \( x_{\text{left}} \) x-coordinate of position of left wheel-axle end |
| \( y_{\text{left}} \) y-coordinate of position of left wheel-axle end |
| \( x_{\text{right}} \) x-coordinate of position of right wheel-axle end |
| \( y_{\text{right}} \) y-coordinate of position of right wheel-axle end |
| \( x_{\text{mid}} \) x-coordinate of middle point between two wheel-axles |
| \( y_{\text{mid}} \) y-coordinate of middle point between two wheel-axles |
2. On-board Velocity and Position Measurement System

2.1. Structure

Two three-dimension (3-D) MEMS gyroscopes and two low cost GPS receivers are used in this on-board measurement system. Fig. 1 is the structure diagram of a rugby wheelchair. One 3-D gyroscope and one GPS receiver are mounted on the axle end of the left wheel, seen in Fig. 1(a), and the other 3-D gyroscope and GPS receiver are on the axle end of the right wheel, showed in Fig. 1(a) and (b).

As shown in Fig. 2(b), one device integrated with a 3-D gyroscope and a GPS receiver is mounted on the axle of the right wheel. The other one is mounted on the axle of the left wheel.

\[ w_{\text{left}} = v_{\text{left}} / r \]

Fig. 1. (a) Front-view of the rugby wheelchair; (b) left side-view of the rugby wheelchair.

Fig. 2. (a) A device integrated with a 3-D gyroscope and a GPS receiver. It is plugged in a recharge socket; (b) two devices are mounted on the both wheel-axle ends.

2.2. Algorithm

A wheelchair with an athlete is a physical example of a dynamic system. The motions of the wheelchair and the athlete are governed by laws of motion that depend upon their current positions and velocities. As the wheel radius is \( r \), the relationship between the rotational speed of the left wheel \( w_{\text{left}} \) and the linear speed of the left wheel \( v_{\text{left}} \) can be written as

\[ w_{\text{left}} = v_{\text{left}} / r \], or \[ v_{\text{left}} = w_{\text{left}} r \] (1)
And the relationship between the rotational speed of the right wheel $w_{\text{right}}$ and the linear speed of the right wheel $v_{\text{right}}$ can be written as

$$w_{\text{right}} = v_{\text{right}} / r, \text{ or } v_{\text{right}} = w_{\text{right}} r$$

(2)

Consider the fact that the difference between $v_{\text{left}}$ and $v_{\text{right}}$ will produce the deflection of the wheelchair. Let the initial deflection angle $\theta_0 = 0$, as diagramed in Fig. 3(b), for any instant $t$, the relationship between the turning angular speed $\omega$ and the deflection angle $\theta$ can be written as

$$\omega = d\theta / dt$$

(3)

As the length between the two wheel-axles is $L$, illustrated in Fig. 3(b), one can obtain the following relations:

$$v_{\text{left}} = v_{\text{mid}} - \omega L / 2, \quad v_{\text{right}} = v_{\text{mid}} + \omega L / 2$$

(4)

For the wheelchair position, the general form can be written as

$$x_{\text{left}} = x_{\text{mid}} - (L \cos \theta) / 2, \quad y_{\text{left}} = y_{\text{mid}} - (L \sin \theta) / 2$$

$$x_{\text{right}} = x_{\text{mid}} + (L \cos \theta) / 2, \quad y_{\text{right}} = y_{\text{mid}} + (L \sin \theta) / 2$$

(5)

(6)

Through measuring the rotational speed and position of the two wheel-axles, one can obtain

$$x_{\text{mid}} = (x_{\text{right}} + x_{\text{left}}) / 2$$

$$y_{\text{mid}} = (y_{\text{right}} + y_{\text{left}}) / 2$$

$$v_{\text{mid}} = (w_{\text{right}} r + w_{\text{left}} r) / 2$$

$$\theta = \tan^{-1} [(y_{\text{right}} - y_{\text{left}}) / (x_{\text{right}} - x_{\text{left}})]$$

$$\omega = (w_{\text{right}} r - w_{\text{left}} r) / L$$

(7)

(8)

(9)

(10)

(11)

Fig. 3. Diagram of on-board velocity and position measurement algorithm. (a) overhead view of the movement of a wheelchair with an athlete; (b) diagram of the movement, describing the variables and the relationship among them.
2.3. EKF Algorithm

The EKF is used in the algorithm for integration positioning in order to provide a continuous and reasonably accurate measuring and positioning service. Let $x_{\text{mid}}, y_{\text{mid}}, v_{\text{mid}}, \theta$ and $L$ be state variables, and $x_{\text{left}}, y_{\text{left}}, w_{\text{left}}, x_{\text{right}}, y_{\text{right}}$ and $w_{\text{right}}$ observation variables. They are collected into two single vectors:

$$s = [x_{\text{mid}} \ y_{\text{mid}} \ v_{\text{mid}} \ \theta \ \omega \ \ L]^{T} \quad (12)$$

$$z = [x_{\text{left}} \ y_{\text{left}} \ x_{\text{right}} \ y_{\text{right}} \ w_{\text{left}} \ w_{\text{right}}]^{T} \quad (13)$$

Suppose that a measurement has been made at time $t_k$ and that the information it provides is to be applied in updating the estimate of the state $x$ at time $t_k$. The measurement interval is $\Delta t$. The following discrete-time equations relate the state at the previous time step $k-1$ to the state at the current time step $k$:

$$s_k = \begin{bmatrix}
1 & 0 & -\Delta t \sin \frac{\theta + \omega \Delta t}{2} & 0 & 0 & 0 \\
0 & 1 & \Delta t \cos \frac{\theta + \omega \Delta t}{2} & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & \Delta t & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix} s_{k-1} \quad (14)$$

The discrete-time observation equation is given by

$$z_k = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & -\cos \frac{\theta}{2} \\
0 & 1 & 0 & 0 & 0 & -\sin \frac{\theta}{2} \\
1 & 0 & 0 & 0 & \cos \frac{\theta}{2} \\
0 & 1 & 0 & 0 & \sin \frac{\theta}{2} \\
0 & 0 & 1 & 0 & L/2 & 0 \\
0 & 0 & 0 & 1 & L/2 & 0
\end{bmatrix} s_k \quad (15)$$

The position measured by GPS may not represent the wheelchair’s current position but these values provide a significant contribution in eliminating the gyroscopic drifts. That is because the kinematics of the user is relatively low (with the speed of less than 10 m/s) and the measurements by GPS are drift-free even though they contain errors caused by the GPS positioning errors. The EKF is implemented and provides the estimation of the errors in position and velocity determinations according to the referencing measurement generated from the GPS. These estimated errors are then used to correct the gyroscopic velocity estimation.

3. Experiments

The low cost on-board velocity and position measurement system for wheelchairs includes two MinimaxX modules. Each of them contains a tri-axis 100 Hz MEMS gyroscope, a low cost 5 Hz GPS receiver and a wireless network transmitter. Fig. 4 shows the two axes positioning results with the reference true position values and EKF filtered position value. The significant drift in gyroscope is greatly eliminated by the integrated GPS.
measurement system, which uses EKF for smoothing the GPS positioning estimations, provides low positioning and velocity error RMS.

4. Conclusion

A low cost on-board velocity and position measurement system is developed for wheelchair sports with two gyroscopes and two GPS receivers. A new algorithm of integrating the gyroscope estimation and GPS positioning has also been developed. The algorithm uses an EKF combining the gyroscope local geographic navigation frame mechanization and the GPS approach together. It improves the positioning update rate from 5 Hz to 100 Hz and maintains the positioning accuracy. Theoretically, this integration method can provide more reliable estimation based on the wheelchair kinematic characteristics rather than simply smoothing the estimations.

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