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Attitude and Position Estimation for a Power Line Inspection Robot

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Abstract: **This paper presents the design of a state estimator for fusing sensor data on a power line inspection robot to obtain position and attitude estimates. The approach taken is a loose coupling of global positioning system (GPS) data with inertial measurement unit (IMU) data and joint angle measurements. The fact that robot is constrained to be on a span is used to reduce the number of degrees of freedom. In this application, a magnetometer cannot provide useful measurement of the earth's magnetic field for attitude estimation because of the proximity to high current carrying transmission lines.**

Keywords: **Power line robot; State estimation; Kalman filtering.**

1 INTRODUCTION

This paper describes the design of an extended Kalman filter for estimating the position and attitude of a power line inspection robot shown in Figs 1 and 2. The robot design has been described in Lorimer and Boje (2012), Rowell and Boje (2012) and Lorimer (2013). The robot has been tested under remote control on out-of-service lines, has been laboratory tested for aspects of autonomous navigation, and has undergone extensive high voltage laboratory testing. Our robot was designed to be light weight for easy field deployment and is able to navigate over typical line hardware including spacers, dampers and suspension fittings. It is also able to navigate over the jumper cable associated with strain towers. This is particularly challenging as the jumper cable may be out of line, is not under tension and may be nearly vertical. The long-term aim of the development is to have a robot that is able to inspect the entire length of a line in an autonomous way.

Accurate location and attitude are important for navigation and inspection tasks and for inspection history. The robot's on-board sensor data can be fused to obtain optimal estimates of the state of the robot. This paper will deal with the GPS (Locosys 66-channel LS23001) and IMU (CH Robotics UM6-LT) fusion with power line design data. Of course, barometric pressure, telecommunication signals and other aiding sources can be added to the state estimation structure.

In normal motion along open stretches of line (illustrated in Fig. 2), the robot can move at speeds of around 1 m/s using driven wheels on both end effectors and during this time, the measured orientation of the robot with respect to the known line direction provides a component of the attitude determination. This only works well when both drive pulleys are in contact with the line. As illustrated in Fig. 3, the robot navigates around obstacles such as spacers, dampers and suspension clamps by gripping with one end effector and then reaching around the obstacle with the other. When a single gripper is on the line (i.e. during obstacle navigation), the line direction can still be detected (as the gripper engages both the driving pulley and the dolly pulley from below the line) but with lower confidence because the two pulleys of a gripper are relatively close together.

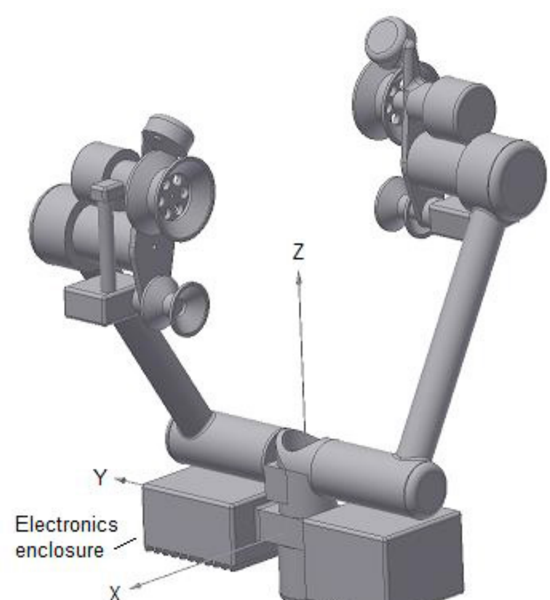

Fig. 1. Render of power line robot

The paper is organised as follows. In Section 2, a scheme based on the TRIAD algorithm is developed to determine the attitude of the robot's platform with respect to the navigation frame. Because the earth's rotation and Coriolis effects can be ignored, an earth-fixed frame that rotates with the earth (navigation frame) can be regarded as the inertial frame. This implementation uses the direction of the line (in the horizontal plane) while the robot is on a span between two towers and the

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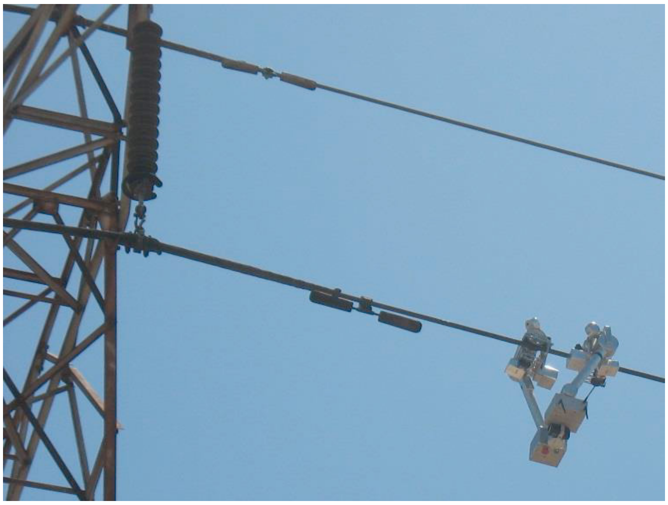

Fig. 2. Power line robot deployed on a single-conductor 132 kV line showing the normal rolling configuration

Fig. 3. Power line robot deployed on a double conductor 220 kV line showing navigation around a spacer

gravity vector obtained from the on-board accelerometer as sources. Section 3 shows that the line slope can be modelled using the line direction and the platform attitude. Section 4 develops an extended Kalman filtering approach to integrating the available measurements to obtain improved estimates of the position and attitude of the platform.

2 ATTITUDE DETERMINATION WITHOUT MAGNETOMETER SIGNALS

In many attitude determination problems a 3-axis magnetometer is used as an aiding source via determination of the direction of the earth's local magnetic field. In the current application a number of problems make this infeasible: The local magnetic field is influenced by proximity to the steel towers and steel-cored conductors; it is difficult to shield the magnetometer from high current, high frequency signals generated by the on-board motor drivers; and in live-line operation there may be significant electromagnetic interference from the line current (for example, at $R = 0.5$ m from a line carrying $I_{\mathrm{RMS}} = 1$ kA, the magnetic field will be $B_{\mathrm{peak}} = \frac{\sqrt{2}I_{\mathrm{RMS}}\mu_0}{2\pi R} = 566\ \mu\mathrm{T}$ compared to the earth's magnetic field strength which in the range of 25 to 65 μT). Even with power-frequency notch filtering and averaging over multiple cycles, with issues such as low signal to interference ratio, quantisation effects, aliasing and the movement of the robot through the induced magnetic field (e.g. because of swinging), use of a magnetic field sensor is not practical. As an alternative, the attitude of the robot can be estimated from the measured orientation of the robot with respect to the known (i.e. surveyed) angle of the projection of the power line onto the horizontal plane, and the measured gravity vector using the TRIAD algorithm (for background, see Hall, 2003; or Tanygin and Shuster, 2007). (QUEST algorithms could be applied if measurement noise is considered.)

The body frame (superscript b) is the frame attached to the robot platform electronics bay. The position and attitude of other robot appendages can be calculated from the platform origin via known joint angles (all joint angles are measured with high resolution encoders). In the body frame, the gravity vector, $\boldsymbol{g}^b$, is obtained from the 3-axis accelerometer assuming no significant forces from acceleration. Low pass filters can be employed to average out the acceleration forces but this must be done with caution if there is simultaneous rotation as the filtering should be in a stationary (inertial/navigation) frame to avoid bias. Notice that because of slow dynamics, there is no practical difference between an earth-fixed frame and an inertial frame. The body frame power-line vector, $\boldsymbol{\ell}^b$, is obtained from the (forward pointing) line joining the two drive pulleys, rotated through the robot's kinematic chain to the platform. Note that in the calculations below, the local line slope is not used because the slope in the navigation frame is not known without the position on the span being known and because the sag is not known. In the navigation frame, the gravity vector is fixed as $\boldsymbol{g}^n = [0 \quad 0 \quad -g]^{\mathrm{T}}$ and the line horizontal component vector is known (from GIS data) as $\boldsymbol{\ell}^n = [\ell_x \quad \ell_y \quad 0]^{\mathrm{T}}$. It is assumed that the line movement (e.g. due to wind) has an insignificant influence on the direction of the line vector.

The TRIAD algorithm sets the first two triads equal to the respective normalised gravity vectors in their respective co-ordinate frames,

$$\boldsymbol{t}_1^b = \boldsymbol{g}^b/\|\boldsymbol{g}^b\|, \text{ and } \boldsymbol{t}_1^n = \boldsymbol{g}^n/\|\boldsymbol{g}^n\|. \tag{1}$$

It then finds the unit normals to the $\boldsymbol{g}$-$\boldsymbol{\ell}$ planes,

$$\boldsymbol{t}_2^b = \boldsymbol{g}^b \times \boldsymbol{\ell}^b/\|\boldsymbol{g}^b \times \boldsymbol{\ell}^b\| \text{ , and}$$
$$\boldsymbol{t}_2^n = \boldsymbol{g}^n \times \boldsymbol{\ell}^n/\|\boldsymbol{g}^n \times \boldsymbol{\ell}^n\|. \tag{2}$$

Finally, the triads are completed by finding the unit normals between these and the corresponding gravity vectors,

$$\boldsymbol{t}_3^b = \boldsymbol{g}^b \times \boldsymbol{t}_2^b/\|\boldsymbol{g}^b \times \boldsymbol{t}_2^b\|, \text{ and}$$
$$\boldsymbol{t}_3^n = \boldsymbol{g}^n \times \boldsymbol{t}_2^n/\|\boldsymbol{g}^n \times \boldsymbol{t}_2^n\|. \tag{3}$$

This process makes the line slope irrelevant as $\boldsymbol{t}_2$ is normal to the vertical plane of the line and $\boldsymbol{t}_3$ is normal to the gravity