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Improved Stewart platform state estimation using inertial and actuator position measurements

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ABSTRACT

Accurate and reliable estimation of the kinematic state of a six degrees-of-freedom Stewart platform is a problem of interest in various engineering disciplines. Particularly so in the area of flight simulation, where the Stewart platform is in widespread use for the generation of motion similar to that experienced in actual flight. Accurate measurements of Stewart platform kinematic states are crucial for the application of advanced motion control algorithms and are highly valued in quantitative assessments of simulator motion fidelity. In the current work, a novel method for the reconstruction of the kinematic state of a Stewart platform is proposed. This method relies on an Unscented Kalman Filter (UKF) for a tight coupling of on-platform inertial sensors with measurements of the six actuator positions. The proposed algorithm is shown to be superior to conventional iterative methods in two main areas. First, more accurate estimates of motion platform velocity are obtained and, second, the algorithm is robust to inherent measurement uncertainties like noise and bias. The results were validated on the SIMONA Research Simulator (SRS) at TU Delft. To this end, an efficient implementation of the algorithm was driven, in real time, by actual sensor measurements from two representative motion profiles.

1. Introduction

The Stewart platform (Stewart, 1965) (see Fig. 1) is a six degrees-of-freedom (DOF) parallel manipulator that is in widespread use throughout various robotic disciplines. The main reasons for this are its relatively low mass, high accuracy, rigidity and support for heavier loads as compared to conventional serial manipulators. Some common applications include manufacturing (Alves De Sousa et al., 2014), surgery (Kratchman et al., 2011; Wapler et al., 2003) and medical rehabilitation (Girone, Burdea, Bouzit, Popescu, & Deutsch, 2001; Liu, Liu, Meng, Zhou, & Ai, 2014). Perhaps the most popular application is that of vehicular motion simulation, e.g., aeronautical flight simulation (Bürki-Cohen, Sparko, & Bellman, 2011).

Given this wide range of applications, obtaining an accurate estimate of a Stewart platform's kinematic state is often of interest. A typical example is the application of advanced control techniques to Stewart platforms, e.g., Davliakos and Papadopoulos (2008), and Pi and Wang (2011). An increasingly relevant application is also that of flight simulator motion fidelity assessment. It is well known that humans perceive inertial self-motion predominantly by means of the vestibular system, which is sensitive to both specific force and angular acceleration (Van Der Steen, 1998). Current efforts to quantify motion fidelity therefore focus on the development and standardization of frequency-domain system identification methods to capture and specify the motion transfer characteristics of contemporary motion cueing systems (Advani, Hosman, & Potter, 2007; Anonymous, 2009). Estimation of the kinematic state of a Stewart platform, however, is inhibited by two particular difficulties. The first is the inference of a Stewart platform's position and attitude from measurements of its six actuator positions (the so-called *forward kinematics* problem). The second is the subsequent inference of platform (angular) velocity and acceleration, as required by many of the typical applications listed here.

The forward kinematics of the Stewart platform have been a subject of study for many decades (Dasgupta & Mruthyunjayab, 2000). Over the years, several authors have shown, for numerous possible platform geometries, that the forward kinematics of a Stewart platform has up to 40 possible solutions (Husty, 1996; Raghavan, 1993; Wampler, 1996). As already acknowledged by Merlet, (Merlet, 1993, 2004), however, a closed-form algebraic method to obtain a single *unique* solution for the platform position and attitude based on only six actuator length measurements does not exist. As a result, a variety of numerical methods to solve the forward kinematics have been developed (Dieudonne, Parrish, & Bardusch, 1972; Merlet, 2004; Zhou, Chen, Liu, Li, & New Forward, 2015). A common limitation of these efforts

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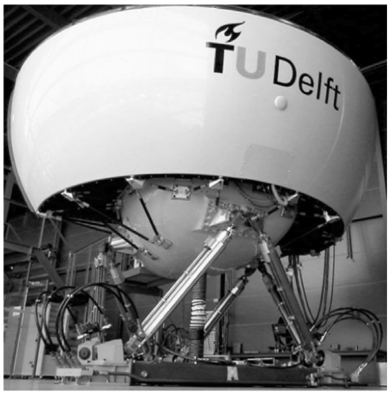

Fig. 1. The SIMONA Research Simulator, using a Stewart platform as the motion providing mechanism Stroosma et al. (2003).

to solve the forward kinematics of a Stewart platform, however, is that they are limited to inference of platform position and attitude *only*. Neither addresses the second problem, namely that of inference of platform (angular) velocity and acceleration. While numerical differentiation of position and attitude is applied to obtain the latter, the presence of measurement noise in physical sensors clearly renders such an approach suboptimal. Nonlinear state observers have therefore also been relied upon to directly evaluate the platform pose and velocity (Chen, Huang, & Fu, 2008; Maged, Bab, & Abouelsoud, 2015). These typically require an explicit model of both platform dynamics and, especially for hydraulically driven platforms, actuator dynamics. While these methods offer some robustness to *model* uncertainties, they lack an inherent mechanism to account for *sensor* uncertainties, e.g., noise and bias. In light of the growing availability of both affordable and accurate inertial sensors (Armenise, Ciminelli, Dell'Olio, & Passaro, 2010), this paper presents a novel approach to estimate the kinematic state of a Stewart platform.

The proposed approach relies on the fusion of on-platform inertial sensors, encapsulated in an Inertial Measurement Unit (IMU), with the six available actuator position sensors. This is accomplished by using an extension of the Kalman Filter (KF) (Kalman, 1960) to nonlinear systems. Through this approach, the need for explicit knowledge of motion platform and actuator dynamics is eliminated, while at the same time incorporating robustness to measurement inaccuracies. The idea of using a Kalman filter-based method for such an application is not new and has been widely demonstrated in, e.g., robotics (Assa & Janabi-Sharifi, 2014; Lin, Komsuoglu, & Koditschek, 2006), aerospace (Lu, Van Eykeren, Van Kampen, De Visser, & Chu, 2015; Mulder, Chu, Sridhar, Breeman, & Laban, 1999), biomedical engineering (Vaccarella, De Momi, Enquobahrie, & Ferrigno, 2013) and power plant control (Hovland et al., 2005). Applications to Stewart platforms, however, remain limited to only a small number of DOFs Louda, Rye, Dissanayake, & Durrant-Whyte (1998); Pool, Chu, Mulder, & van Paassen (2008). More recently, the Iterated Extended Kalman Filter (IEKF) (Gelb, 1974) was applied to extend the sensor fusion scheme to all six DOFs of the Stewart platform Miletović, Pool, Stroosma, Chu, & van Paassen (2005). The current work applies the more advanced Unscented Kalman Filter (UKF) (Julier & Uhlmann, 2004), suitable for more nonlinear problems, and presents both the simulation and real-time experimental validation of the proposed state reconstruction algorithm.

The paper is structured as follows. First, a brief introduction to the Stewart platform and its kinematics is provided. Then, the proposed state reconstruction algorithm is introduced, followed by a verification of the algorithm on the basis of computer simulations. Subsequently, the validation of the proposed algorithm on the SIMONA Research Simulator (SRS), using a real-time implementation driven by actual sensor measurements, is presented. This validation also includes a comparison to an iterative scheme commonly applied to estimate the kinematic state of Stewart platforms. Finally, a brief discussion is provided and the paper is concluded.

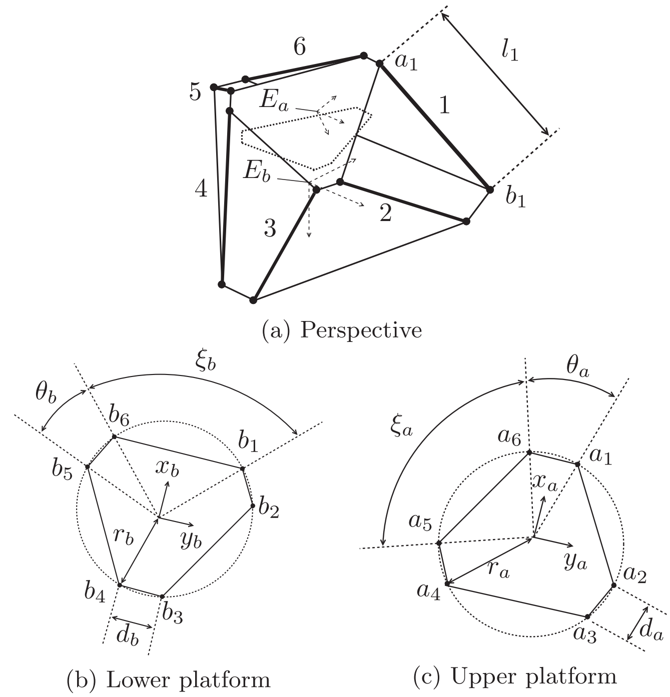

Fig. 2. The geometry of a Stewart platform.

2. Stewart platform kinematics

The kinematics of a Stewart platform are defined by its geometry, shown in Fig. 2. The coordinates of the joints on the lower (Fig. 2b) and upper (Fig. 2c) platform, in turn, determine the geometry of the platform. The locations of these joints are conveniently specified with respect to the centroids of the joints on the lower and upper platform. These centroids are typically referred to as the Lower Gimbal Point (LGP) and Upper Gimbal Point (UGP), respectively. The origins of two right-handed reference frames E_a and E_b are attached to the UGP and LGP, respectively. All joints on the lower and upper platforms lie equidistantly spaced with a certain distance (i.e., d_a or d_b) in pairs on a circle with a given radius (i.e., r_a or r_b), such that the coordinates of each joint (i.e., $\boldsymbol{a}_i$ and $\boldsymbol{b}_i$) can be derived from basic trigonometry. Note that even though this specific configuration of the Stewart is used in the current work, the authors foresee no issues in applying the proposed methodology to any non-singular platform geometry.

The length of each of the connecting elements between the joints then follows from the geometry as:

$$l_i(\boldsymbol{c}, \boldsymbol{\Phi}) = \|\boldsymbol{c} + T_{ba}(\boldsymbol{\Phi})\boldsymbol{a}_i^a - \boldsymbol{b}_i^b\| \quad \forall \ i \in [1, \ldots, 6] \tag{1}$$

The vector $\boldsymbol{c}$ defines the position of the origin of reference frame E_a with respect to E_b and is expressed in Cartesian coordinates as:

$$\boldsymbol{c} = [x \ \ y \ \ z]^\top \tag{2}$$

T_{ba} is the transformation matrix that describes the transformation $a_i^a \to a_i^b$ and therefore Eq. (1) depends on the attitude of frame E_a with respect to E_b. Here, attitude is represented using the Euler-Rodrigues quaternion formulation Phillips and Hailey (2001); Soijer (2009) for numerical efficiency. As such, the attitude vector is:

$$\boldsymbol{\Phi} = [e_0 \ \ e_x \ \ e_y \ \ e_z]^\top \tag{3}$$

and the transformation matrices T_{ab} and T_{ba} can subsequently be defined as Phillips and Hailey (2001):