INTEGRATED MOTION MEASUREMENT OF MULTIBODY SYSTEMS AND FLEXIBLE VEHICLE STRUCTURES

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Abstract: Integrated navigation systems based on inertial sensors and GPS are well-established devices for vehicle guidance. The system design is traditionally based on the assumption that the vehicle is a rigid body. However, generalizing such integrated systems to rigid multibody or even more to flexible structures is possible. It is based on distributed sensors and provides an interesting basis for motion control and system identification. The kernel of the integrated system consists of an observer that estimates the motion state of the mechanical structure. The paper presents the multibody and the flexible structure approach as well as first motion estimation results.

Keywords: Navigation systems, observers, data fusion, inertial sensors, robotics, large structures, kinematics.

1. INTRODUCTION

Integrated navigation systems based on gyros, accelerometers, and satellite navigation receivers are well-established devices for vehicle guidance. The central system design requires modelling the kinematics of the vehicle, which is traditionally assumed to be simply a single rigid body (Farrell and Barth, 1999). However, this premise is no longer reasonable if the system layout includes sensors being distributed spaciously over the vehicle and if in parallel the vehicle changes its shape due to structural flexibilities (e.g. large aircraft) or due to a multibody structure (e.g. mobile robots). In this case, generalizing the theory of integrated navigation systems becomes necessary. This approach is outlined in the following and provides not only an interesting basis for an extensive motion control but also for system identification.

Firstly, Section 2 presents the principle of integrated navigation systems and illustrates that this is more precisely a matter of integrated motion measurement of a given mechanical structure. Including simulation and experimental results, Section 3 contains a synopsis of the extended system theory for multibody structures, and Section 4 for flexible vehicles. Section 5 summarises the outcome and specifies future work.

2. INTEGRATED MOTION MEASUREMENT

The idea of integrated navigation systems consists of combining complementary motion measuring principles and of utilising their specific advantages: Inertial sensors like classical or like modern micro-electro-mechanical gyros and accelerometers are used to obtain reliable signals being usable for a short period of time and allowing a high resolution with time. On the other hand, less dependable sensors (often with relevant signal delays) like GPS receivers and radar units are used due to their good long-term accuracy. The kernel of integrated navigation systems is an observer (typically realised by an extended Kalman filter (Gelb, 1989)) blending the sensor signals and estimating the relevant vehicle motion (Farrell and Barth, 1999). Besides the sensor combination employed, the theoretical basis for the filter requires a kinematical model of the vehicle motion considered, which has to be set up individually (nevertheless, established models exist (Wagner and Wieneke, 2003)). This model describes the standardised dynamics of the vehicle, mostly by means of specific forces, i.e. accelerations, and of angular rates. Hence, there are no dynamometers or mass properties needed in this approach.

There are different system integration variants of such navigation systems (Wagner and Wieneke, 2003). However as mentioned, they all have the observer principle in common with the signal flow depicted in Figure 1: Reliable sensors of high availability permit a good resolution with time (like accelerometers and gyros) and provide the input signal vector $\mathbf{u}$ generating the vehicle motion considered (state vector $\mathbf{x}$). Based on $\mathbf{x}$ and $\mathbf{u}$, so-called aiding sensors (being mostly attached to the vehicle) like a GPS receiver or a laser altimeter provide measurement signals (vector $\mathbf{y}$) with good long-term accuracy. Furthermore, there is a parallelism between the performance of the real moving structure and its aiding equipment on one side and a motion and aiding simulation on the other side. The simulation takes place within the actual observer, it is based on two kinematical models, and it leads to estimates $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ of $\mathbf{x}$ and $\mathbf{y}$. The first model describes the motion considered and is a set of ordinary nonlinear differential equation (being solved numerically); the second one emulates the aiding:

$$\dot{\hat{\mathbf{x}}}(t) = \mathbf{f}\left(\hat{\mathbf{x}}(t), \mathbf{u}(t)\right), \tag{1}$$

$$\hat{\mathbf{y}}(t) = \mathbf{h}\left(\hat{\mathbf{x}}(t), \mathbf{u}(t)\right). \tag{2}$$

Due to sensor, modelling and initialisation errors, the estimates show inaccuracies, which increase usually with time t and which require therefore a correction: The feedback of the difference between $\mathbf{y}$ and $\hat{\mathbf{y}}$ serves as input of a compensation device adjusting $\hat{\mathbf{x}}$ by $\mathbf{K}(\mathbf{y}-\hat{\mathbf{y}})$. The correction matrix $\mathbf{K}(t)$ is typically part of the algorithm of an extended Kalman filter, however sometimes alternatives like particle filters are used as well (Yi and Grejner-Brzezinska, 2006).

Independently from the observer type, the system stability requires that $\mathbf{x}$ is completely observable. Reflecting the type and geometrical array of the sensors used (see below), the content of $\mathbf{f}$ and $\mathbf{h}$ determines this property. The observability is ensured if the matrix

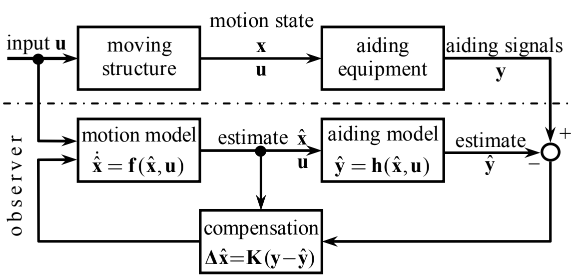

Fig. 1. Observer principle used for signal fusion.

$$\mathbf{\Xi} = \left[\mathbf{H}^T \quad \mathbf{F}^T \cdot \mathbf{H}^T \quad \ldots \quad \left(\mathbf{F}^T\right)^{n-1} \cdot \mathbf{H}^T\right] \tag{3}$$

employing the Jacobians $\mathbf{F}(\mathbf{x}(t),\mathbf{u}(t))$ and $\mathbf{H}(\mathbf{x}(t),\mathbf{u}(t))$ of $\mathbf{f}$ and $\mathbf{h}$ has full rank n (Gelb, 1989) with n being the number of state variables in $\mathbf{x}$. As $\mathbf{F}$ and $\mathbf{H}$ vary with time, it is possible that phases of complete observability alternate with phases of reduced observability. This applies especially for the classical combination of inertial sensors with a single antenna GPS receiver during periods of steady vehicle motion (Hong *et al.*, 2000). To solve this problem effectively, several aiding antennas are required that have to be distributed spaciously over the vehicle (Wagner, 2003).

Assuming consequently distributed sensors, the idea of a single rigid body being the moving structure becomes doubtful. On the other hand, the theory of motion modelling for integrated navigation can be extended to rigid multibody systems and also to flexible structures. This is outlined in the next two sections.

3. RIGID MULTIBODY SYSTEMS

The kinematics (i.e. time variable geometry) of rigid multibody systems can be conveniently and completely described with a minimal set of generalised coordinates $\mathbf{q}(t)$ and minimal set of (pseudo) velocities $\boldsymbol{\pi}(t)$ (Bremer and Pfeifer, 1992). In case, the system is holonomic, $\dot{\mathbf{q}}$ and $\boldsymbol{\pi}$ are identical. Otherwise, usual mechanical structures show a linear relation between $\dot{\mathbf{q}}$ and $\boldsymbol{\pi}$, which reduces the number of degrees of freedom from the level of position/attitude to the level of velocities. Employing the Jacobian $\mathbf{J}_q$ and the term $\mathbf{q}'$, this equation reads in general:

$$\dot{\mathbf{q}} = \mathbf{J}_q\left(\mathbf{q},t\right)\boldsymbol{\pi} + \mathbf{q}'\left(\mathbf{q},t\right). \tag{4}$$

Assuming a rigid multibody system equipped with μ accelerometers j (i.e. $j = 1, \ldots, \mu$) and ν gyros k (i.e. $k = \mu+1, \ldots, \mu+\nu$), each being strapped down to one of the rigid components, the following general relations describe firstly the position ${}_i\mathbf{r}_j$, the velocity ${}_i^i\dot{\mathbf{r}}_j$, and the acceleration ${}_i^i\ddot{\mathbf{r}}_j$ of an accelerometer attachment point. In these relations, the subscript on the lower left side indicates the coordinate system for representing the respective vector, whereas the upper left subscript describes that the vector has been differentiated with respect to the indicated coordinate system. In both cases, an inertial frame i is employed here:

$${}_i\mathbf{r}_j = {}_i\mathbf{r}_j\left(\mathbf{q},t\right), \tag{5a}$$

$${}_i^i\dot{\mathbf{r}}_j = \mathbf{J}_{r_j}\left(\mathbf{q},t\right)\dot{\mathbf{q}} + \frac{\partial\, {}_i\mathbf{r}_j}{\partial t} \quad \text{with} \quad \mathbf{J}_{r_j} = \frac{\partial\, {}_i\mathbf{r}_j}{\partial \mathbf{q}}, \tag{5b}$$

$${}_i^i\ddot{\mathbf{r}}_j = \mathbf{J}_{r_j}\left(\mathbf{q},t\right)\ddot{\mathbf{q}} + \frac{\mathrm{d}\mathbf{J}_{r_j}}{\mathrm{d}t}\dot{\mathbf{q}} + \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial\, {}_i\mathbf{r}_j}{\partial t}\right). \tag{5c}$$

The next equations describe the attitude ${}_i\boldsymbol{\gamma}_k$ (e.g. three Euler angles), the angular rate ${}_i\boldsymbol{\omega}_k$, and the angular acceleration ${}_i^i\dot{\boldsymbol{\omega}}_k$ at a gyro attachment point. As large rotations ${}_i\boldsymbol{\gamma}_k$ have not the character of a Cartesian vector like ${}_i\mathbf{r}_j$ or ${}_i\boldsymbol{\omega}_k$, only similar relations between the atti-