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Integrated motion measurement illustrated by a cantilever beam

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ABSTRACT

The combination of inertial sensors and satellite navigation receivers like those of GPS (Global Positioning System) represents a very typical integrated navigation system. Integrated navigation is the most common example of integrated motion measurement determining the translational and angular position, velocity, and acceleration of a vehicle. Traditionally, this object is assumed to be a rigid body and the signals of its closely spaced sensors are referenced to a single point of the structure. During periods of low vehicle dynamics such common navigation systems typically show stability problems due to a loss of observability of some of the motion variables.

The range of applications for integrated navigation systems can be expanded due to the continuously increasing performance of data processing and cheap sensors. Further, it can be shown that the stability of such a navigation system (i. e. of the motion observer employed for the system, typically a Kalman filter) can be sustained by distributing appropriately additional sensors over the vehicle structures at distinct locations. This comprises the compensation of drift effects of the system by adding sensors that are drift-free and the guarantee of the observability of all estimated motion components. Large structures like airplanes, space stations, skyscrapers, and tower cranes with distributed sensors, however, have to take the flexibility of the structure into account. This includes an appropriate kinematical model of the structure. In this case, the theory of integrated systems has to be expanded to flexible structures. On the other hand, the additional system information obtained can be used not only for vehicle guidance but also for structural control.

Within this work individual kinematical models especially of a cantilever beam, idealizing e.g. the wing of an airplane, are developed and investigated with regard to the observability of the motion variables to guarantee a stable integrated system behaviour. Finally, the application and verification of integrated measurement systems for flexible structures is shown by experiments.

1. Introduction

Integrated navigation systems have long been thought of as expensive and difficult to handle with respect to the highly sophisticated gyro technology and a liability to numerical errors. However, the importance of classical inertial sensors is now decreasing in favour of micro-mechanical and optical ones. Sensor fusion is typically performed by mathematical estimation algorithms. These algorithms can be implemented today on efficient microprocessors. The usage of multiple

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sensors reduces the error-proneness of integrated navigation systems. This allows to combine simpler, cheaper sensors without decreasing the system performance or to improve numerically the results of the estimation algorithms.

In view of the available technologies, integrated navigation systems have become interesting for day to day commercial platforms and are used e.g. in car navigation systems and no longer almost exclusively in military or aviation systems. Furthermore, integrated navigation devices for vehicle guidance are, in principle, the most common example of an integrated motion measurement system which is the subject of this article.

Typically, an integrated navigation system consists of an Inertial Measurement Unit (IMU), a combination of three accelerometers and three gyros, and a single GPS receiver. All these sensors detect motion components of different physical meaning. This means in general, that integrated motion measurement systems are combining signals of various sensor types in order to estimate an unknown motion state of a vehicle or a moving mechanical structure. Traditionally, for these systems the vehicle is assumed to be a single rigid body with six motional degrees of freedom to be determined [5]. During periods of low vehicle dynamics (e.g. almost constant translative velocities) the common integrated navigation systems show, however, stability problems due to a decreasing observability of the motion states. On the other hand, the stability of such a navigation system (i. e. of the motion observer employed for the system, typically a Kalman filter) can be sustained by distributing appropriately additional sensors over the vehicle structures at distinct locations, which have to be determined separately [32]. This comprises the compensation of drift effects of the system by adding sensors that are drift-free and the guarantee of the observability of all estimated motion states. In the case of distributed sensors and notable elastic deformation of the vehicle or structure, the rigid body assumption must be dropped. This approach therefore takes the distributed sensors and the flexibility of the structure into account.

Integrated systems, as mentioned above, are fusing different measurement signals by combining their advantages and blinding out their drawbacks. For instance, gyros and accelerometers are used to obtain reliable signals with a good time resolution. On the other hand, aiding sensors like radar units (vehicle external aiding) and strain gauges (vehicle internal aiding) are known to be at least mid-term accurate under controlled environmental conditions (a long-term accurate strain sensor type could be Fibre Bragg Grating sensors [11]). Furthermore, the kernel of the integrated systems typically consists of an (extended) Kalman filter that estimates the interesting motion state of the structure. Apart from the sensor combination, a kinematical model of the vehicle must be provided as the Kalman filter is a model based observer scheme. Even though the system has to be modelled individually for every vehicle, the effort is limited as well established modelling techniques exist [32]. The kinematical model captures the standardized dynamics of the vehicle by means of specific forces, e.g. accelerations and angular rates. Neither dynamometers nor mass and stiffness properties are needed in this approach.

The progress of classical integrated navigation systems to integrated motion measurements is shown in the following. As described in Wagner [32,33] the classical rigid body assumption of integrated navigation system was expanded to rigid multibody systems and tested by simulations and experiments considering an integrated measurement system with external aiding. The approach for integrated measurement system on flexible (i. e. elastic) structures was described theoretically in Wagner [32]. This theory was applied and proven on several different integrated measurement systems by simulations [20].

In this article, the experimental verification of integrated measurement systems on flexible structures is presented employing a pure internal aiding (here strain gauges) which is possible for the elastic cantilever beam considered. Considering that the reconstruction of elastic deformations employing strain gauges is an established methodology [6,22,16], the novelty of the paper at hand lies in the application of this approach to integrated motion measurement systems (like integrated GPS navigation systems) and in the combined use of gyros, accelerometers and strain sensors: such integrated systems considering the flexibility of the structure and employing an observer model using these three sensor types are not state of the art [23] and will therefore be investigated in this article. Future experiments will have to verify integrated measurement systems on flexible structures including rigid body movements which have already been investigated by simulation [20].

The example of the motion of an elastic cantilever beam being considered here is meant to be an approach to obtain motion measurements of a wing of a large airplane during flight. This investigation aims not only at an extensive motion control but also on system identification and structural health monitoring.

In the following, the basics of integrated navigation and motion measurement systems will be explained shortly in Section 2. Section 3 generalizes the theory of integrated navigation systems for flexible structures. Furthermore, the kinematical models of the cantilever beam considered are presented. The concept of kinematical unit deformations required and the placement of the distributed sensors is discussed in Sections 4 and 5, respectively. The experimental setup of the cantilever beam and the obtained results are shown in Section 6. Section 7 completes the article with a conclusion of the presented work and future topics to be investigated.

2. Basics of integrated motion measurement

The following subsection 2.1 outlines the observer principle which is the basis for integrated motion measurement systems. The implemented estimator, the so-called Kalman filter, belongs to the field of optimal estimation and will be presented in subsection 2.2. Fundamental conditions for the observability of linear systems are also given in subsection 2.3.