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Precise relative positioning in machine swarms

In addition to automatic or semi-automatic guidance of individual machines, guidance of machine swarms is an increasingly important topic. An essential requirement for this is, especially if the machines are cooperating with each other, to know the precise relative position between the machines and to determine the exact orientation of attachments or devices in relation to the machine. To ensure this task even under difficult environmental conditions with poor GNSS (Global Navigation Satellite System) reception, various technological approaches are possible. These approaches will be presented in this article.

Keywords
Tracking, communication structures, cooperative machine operation, sensor fusion, GNSS, INS, optical flow, ad-hoc mobile networks, relative positioning

Abstract
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With the increasing automation of mobile machines and the progressive use of swarms of machines the precise relative position in addition to the absolute position of the machines as well as of their attachments becomes a mayor role. This is especially necessary to guide machines with different tasks in precise formations. In addition, the determination of the relative positions of the machines must be guaranteed in case of partial failure or poor reception of the GNSS receiver, for example to prevent collisions between the machines. Possible options to stabilize the solution of the GNSS receiver are to couple the GNSS data with the information of an Inertial Measurement Unit (IMU), or with the information of an imaging system which calculates the movement based on motion estimation. A further possibility for improvement, which is presented in this article, is the so-called method of swarm localization, in which the GNSS raw data of each swarm participant has to be exchanged within the swarm by a mobile ad-hoc network. By the use of special filters it is possible to eliminate bad signals to calculate an improved relative position. In the following the test vehicles as well as the fundamental sensory structure are presented briefly, before discussing the approaches of the individual technologies.

Technical equipment

In addition to the flexible research platform comRoBS presented in issue 3.2010 [1] the unmanned helicopter testbed ARTIS (Autonomous Rotorcraft Testbed for Intelligent Systems) by the DLR-Institute of Flight Systems and quadrocopters by the Ascending Technologies GmbH (**Figure 1**) are used for the experiments.

These are in addition to their individual actuators and sensors for the project relevant studies equipped with a unified system, which consists of a navigation computer for data processing, an inertial measurement unit and a communication system for exchange of GNSS raw data. Moreover the testbeds are equipped with a wireless connection for data access and debugging. The testbed ARTIS is further equipped with a computer for image processing and with the corresponding system of two cameras as a composite system for motion estimation.

Swarm Positioning using GNSS

For the coordination of different vehicles, which act within a cooperation respectively swarm, the knowledge of absolute position of the swarm participants and relative position to each other, i. e. the baseline between the vehicle reference position, is necessary. A simple way to obtain the baselines is to compute the vectorial difference of absolute positions. These can be compute by using GNSS. In the case of standalone GNSS, i. e. there are no aiding information from reference stations available, the accuracy often doesn't fit the requirements. To cope with this effect, all swarm participants will share their GNSS range measurements using a wireless ad-hoc communication (**Figure 2**). So every rover will be able to use the measurements of all other to calculate absolute and relative positions of the whole swarm using a differential approach. This principle is similar to differential techniques, which apply to the usage of reference station. In contrast to GNSS reference station applications, within the swarm more than two participants are cooperating and that the position of all participants is time variant.

Fig. 1

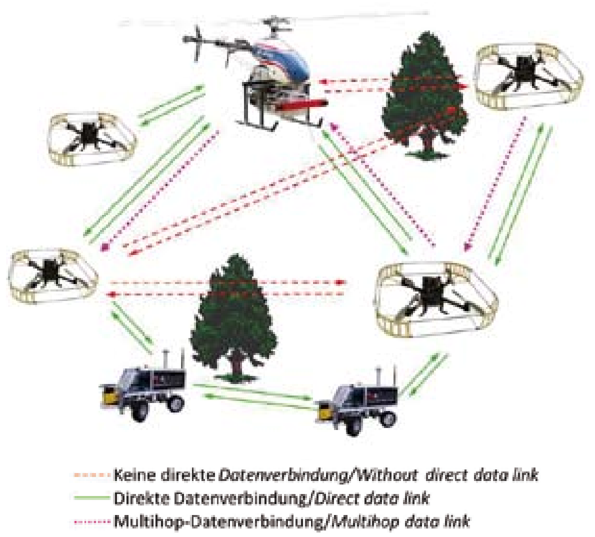
comRoBS, DLR ARTIS, AscTec Pelican Quadrocopter (LTR)

Integration of IMU/GNSS including Failure Detection and Exclusion Methods

Additionally to the absolute and relative position of the participants of the swarm the complete state of the vehicle, i.e. position, velocity, attitude and heading is of interest, when thinking about vehicle guidance and control applications. In order to determine the complete rover state vector, the UGV and UAV described above will be equipped with an Inertial Measurement Unit (IMU), developed and built up by the Institute of Flight Guidance of the Technische Universität Braunschweig (**Figure 3**). The IMU is based on Micro-Electro-Mechanical-System (MEMS) sensors to measure the rover accelerations and turn rates. The measured data are integrated to get the vehicle's position, velocity, attitude and heading; this information is of high-frequency.

Due to characteristics of the system the increasing, time-dependent failure is compensated by coupling the IMUs for example with GNSS-position information within a coupling filter (Kalman-filter). The described concept provides a tight coupling of IMU, GNSS and visual data with GNSS raw measurements for IMU adding. This concept has the advantage that also aiding with less than four GNSS measurements is possible.

Fig. 2



Mobile Ad-hoc-network

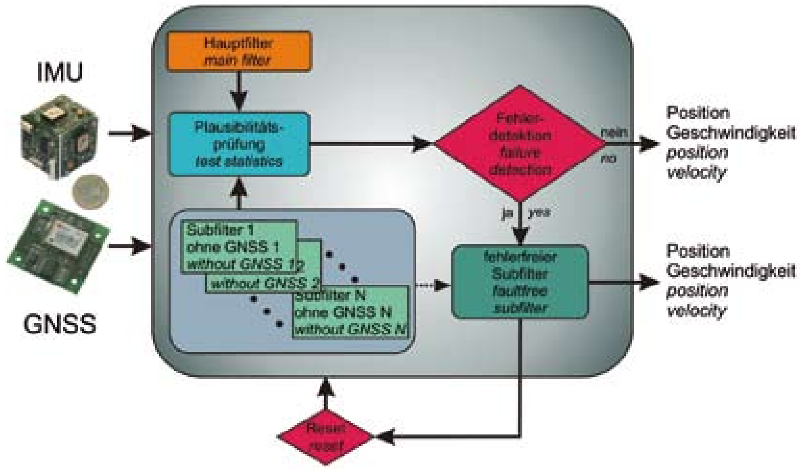
In order to detect degraded GNSS signals or measurement errors a GNSS signal monitoring is conducted using inertial measurements [3]. Therefore multiple coupling filters (N + 1, N = number of GNSS measurements) are running parallel forming a filter bank, as depicted in **Figure 3.** One filter acts as main filter, using all GNSS measurements. The other N subfilters omit one measurement. By applying statistical tests based on the results of the main and sub filters a faulty measurement could be detected and excluded from further processing (Failure Detection and Exclusion, FDE).

Vision-aided relative localization

With small and lightweight cameras and powerful computer systems, image processing techniques gain importance onboard mobile systems. Basis for the localization with the help of cameras are modern calculation methods that derive the ego-motion of the camera from the recorded image sequences in real-time. This is done by the identification of significant image features with unique and recognizable patterns, e.g. high-contrast edges and corners of the recorded objects, and their tracking over time within a video sequence. With the characteristics of the motion patterns from a multiplicity of these image features, the ego-motion of the camera can be determined. With that, the localization filter bank avails an additional sensor to compensate the disadvantages of GNSS and IMU [2]. The methods and algorithms for a full integration of cameras into a reliable and robust navigation system are topics of actual research.

Initially, data derived from environmental image sequences provides a set of features and their movement between different images. Since the described project shall enable localization in arbitrary and also unknown environments, no comparison is carried out between the recorded images and prior knowledge from corresponding maps. Hence, only the relative orientation between two image recordings is determinable from feature movements. This means that the image processing system determines relative movements similar to an inertial system and that the integration of these movements into positions accumulates a contouring error. Additionally, the problem of scale-invariance is existing, i.e. the direction of movement is desirable but without its absolute size when using exactly one camera. By using two cameras as in this project or more, the camera

Fig. 3



Filter bank architecture

movement can be determined with absolute size. This is only valid if enough close objects are present in the images. The eligible distance span is dependent on the stereo or multi-camera setup and ranges approximately between 10 m and 40 m with the employed system.

Mobile Ad-hoc Communication

To improve the positioning solution the GNSS raw data of each participant has to be exchanged as quickly and as safely as possible. In addition, the system must react very flexible to the dynamic changes in the network topology and compensate for example the loss of individual swarm participants. Due to the external conditions also the transmitting and receiving power as well as the antenna technology is limited. Since the individual participants are exchangeable, a system is needed which is organized decentralized. For such tasks so called "Mobile ad-hoc networks (MANet)" or mesh networks are predisposed. With special routing algorithms, which respond dynamically to changes in network topology, an efficient data exchange can be achieved. The data exchange can be realized directly and indirectly through intermediate stations. **Figure 2** shows a possible constellation of the test vehicles used in the project, where some of the participants can directly communicate and others only indirectly through one or more intermediate stations.

In the field of mobile ad-hoc networks various trends and approaches can be found [4]. They are usually specific designed to the particular requirements (number of participants, energy consumption, range, etc.), so that special routing methods are used. At first, they can be differentiated as proactive and reactive algorithms and mixed forms, the so-called hybrid methods. A further method, if information about the location is known, is a position-based routing method. Depending on the situation all methods have advantages and disadvantages in relation to, for example, the time needed to explore the network structure or the data overhead required for the exchange of network information. The objective therefore it is to include several routing methods into one system and then dynamically selecting the most appropriate method by recognizing the situation. A further challenge is the synchronization of the machine swarm. The required real-time processing of the raw data for all participants has also high demands on a time-effective data exchange. In the project the wireless standard IEEE 802.15.4 is used, which is particularly suitable because of the low latency for establishing a connection in dynamic networks.

Summary

The technological challenge of the approach presented in this article for precise relative positioning in machine swarms is mainly in the first-time combination of all presented approaches in one system. In addition further challenges are the technical limitations of the test vehicles as well as the requirement for implementation with affordable components, as the demand for low weight and low power consumption. Experiences from previous projects have demonstrated the suitability of the individual approaches.

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