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Data exchange within clusters of mobile machines for real-time positioning

For controlling mobile machines which are operating on the same task, as well as for automatic or autonomous navigation of machines, positioning of them is a mandatory requirement. Therefore it is necessary that each participant of a machine group is able to compute at nearly every time, where the other participants are and how their current status is defined. To fulfill this requirement a high frequency data exchange of the GNSS raw data from all experimental vehicles is realized using a mobile ad hoc network. The exchanged information is used to compute the relative and absolute position of all participants for each node to each other simultaneously. Additional sensor data, like INS measurements are further used to improve the positioning accuracy.

Keywords
Machine cluster, communication, tracking, mobile ad-hoc networks, GNSS, INS, relative positioning

Abstract
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The increasing automation of mobile machines, the progressive use of machine groups and the requirement for a precise relative positioning of the machines to each other – even under insufficient reception of the GNSS-Signal (Global Navigation Satellite System) – requires new systems and technologies. These are especially necessary to precisely coordinate a machine cluster in a formation to cooperate in different tasks. In addition, a determination of relative positions must be ensured, for example, to prevent collisions between the machines, especially if the signal reception of the GNSS receiver is not reliable. One way to improve the position solution is offered by combining the GNSS position solution with the measured data of an inertial measurement unit (IMU). One approach to determine the relative position of the participants among themselves is called cooperative positioning, wherein the raw GNSS data packets are exchanged between the individual stations over a mobile ad-hoc network. Based on the GNSS raw data of the machine cluster the approach allows each participant to calculate both, the position of the other participants as well as the relative position of the swarm participants to each other. In addition, if necessary, the approach can be used to determine the relative position with partial shading of individual swarm participants, by involving the shared datasets in the processing of the developed swarm positioning algorithm. **Figure 1** shows two of the test vehicle used during the experimental trials. The left is the self-developed UGV „comRoBS“ (unmanned ground vehicle) of the Institute for Mobile Machines and Commercial Vehicles (IMN) [1] and on the right a quadrocopter type Pelican (Manufacturer: Ascending Technologies), operated by the Institute of Flight Guidance (IFF) at the TU Braunschweig, is shown.

As part of the research project NExt UAV (German acronym for: "Navigation for exploration with UAVs at low altitude in disaster Scenarios") [2] basic technologies have been tested to operate a mobile ad hoc network in a heterogeneous machine

Fig. 1

Experimental tests for data exchange between UGV and UAV (Photo: TU Braunschweig) group. Furthermore strategies have been investigated which can ensure a reliable data exchange. A major aim for the development was to ensure the complete exchange of GNSS raw data from two UGV units and up to five air units (UAV – unmanned aerial vehicle), that are spread across the selected application area. The data exchange should take place with a frequency of 1 Hz in order to achieve an adequate update rate for determining the position. In the targeted scenarios and tasks, such as exploration of unknown areas, typically formations are used in which the machine cluster is distributed over a few hundred meters. In an urban environment it is therefore necessary that messages are transmitted via several intermediate links, if no direct connection or only an insufficient connection between the machines exists. The frequent topology changes caused by the mobility of the individual participants as well as the varying amount of data to be exchanged, requires that the communication links are checked with each cycle (1 Hz) and adjusted if necessary. In order not to limit the overall system functionality due to the failure of individual participants, explicitly no central coordinator is used. From the described scenario technical constraints arise for both, the used hardware as well as for the implemented algorithms.

To fulfill the requirements, like the incurred demand of data and the needed transmitter range, wireless modules were chosen, which work in the ISM band at 2.45 GHz. These are very inexpensive, freely usable and achieve a maximum transmission rate of 250 Kbit/s [3]. The algorithms for data exchange are set up on top of the physical layer of the wireless standard IEEE 802.15.4.

The commercial radio modules are mounted on a self-developed carrier board and are therefore easily replaceable. They are based on an ATMEGA128 microcontroller for temporarily storing the raw data and for controlling the communication module. Due to the direct connection to the radio modules hardware time-critical tasks can be performed without the disturbing influence of other processes almost close to real time. The data exchange with the main processor board based on an Intel Atom processor with 1.6 GHz as well as the power supply is realized via an USB connection. The main processor board is connected to a LEA-6T u-blox GNSS receiver which provides the GNSS raw data, as well as a self-developed IMU of the Institute of Flight Guidance (IFF) with a cuboid form which has an edge length of 32 mm, a weight of 40 g [5] which is suitable for use in small flight units. The software used on the main processor board for the processing of the single and swarm position solution as well as for data fusion and data processing is implemented in C++ under Linux. Key criteria for the selection of the computer architecture for the UAV type Pelican were the small size (Pico ITX, 100 x 72 mm) and the low energy consumption of the system.

Swarm positioning

Due to the targeted catastrophic scenarios within the research project NExt UAV, GNSS based positioning technologies have been developed, assuming that there is no local ground based infrastructure like networks of GNSS reference stations available. Thus by default, only GNSS code measurements are available for providing positioning services for the single participants. Regarding GPS correction information SBAS (Satellite Based Augmentation System) can be applied, which is not depending on ground infrastructure [4]. For calculating the current positions of the single UAV and the UGV swarm members a method has been developed that uses all known GNSS-pseudorange-measurements at one epoch that have been exchanged using a permanent data link between all swarm members as described in the following. The basic principle is based on calculating double differences of the GNSS code measurements, a method similar to that of using GNSS reference stations. For the given application there are two major challenges to deal with. First the number of involved receivers is higher compared to applications using reference stations (usually one user and one reference station). Second the positions of all involved user receivers is time variant and none of them is known with a high precision like the one of a reference station. A derivation and detailed explanation of the derived and implemented algorithm can be found in [5].

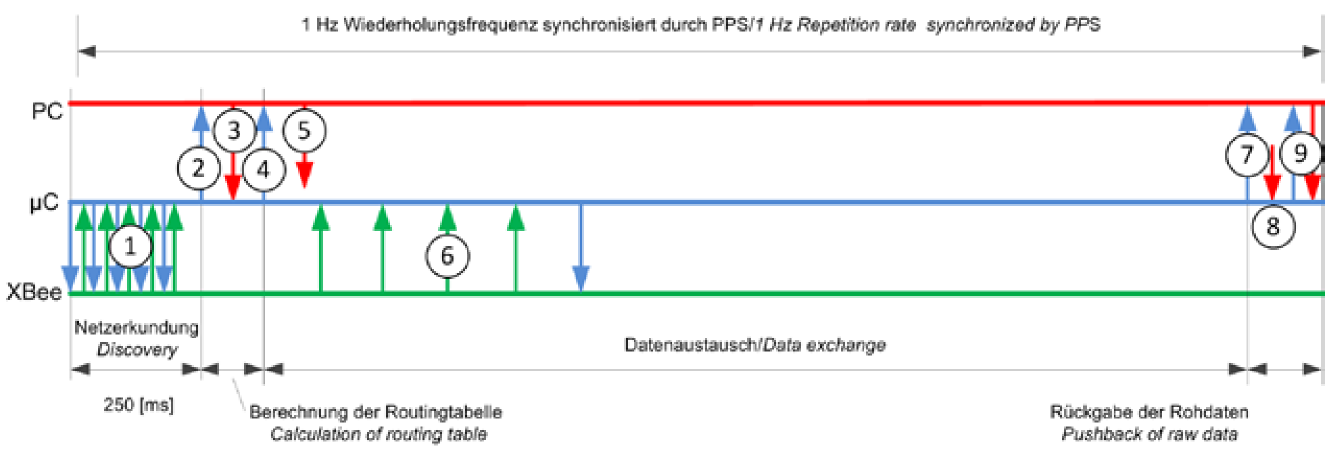
Communication design

During the project, various approaches for data exchange were studied. Under the premise of not using a coordinator, as already mentioned, two methods can be considered for the communication principle. One possible approach is based on choosing random transmission times with an individual scan of the transmission medium for free access. In contrast a time synchronized process allocates the transmitters to a predefined time slot in which a communication is authorized. [6]

The first method was successfully established in experiments with small network sizes. For larger networks, however, the number of additional necessary messages increased disproportionately, due to data collisions. Therefore, this approach has been discarded and the time-slot-based approach has been preferred at which the communication is managed respectively synchronized among the individual devices in a proper manner. For this purpose, the second-configurable trigger signal from the LEA-6T GNSS receiver is used, which corresponds with a frequency of 1 Hz to the PPS signal (pulse per second). This concept allows synchronizing the clocks of the swarm, so that a communication is based on fixed time intervals. The necessary allocation of time ranges for each machine is solved by assigning a unique serial number of the hardware to a unique network ID.

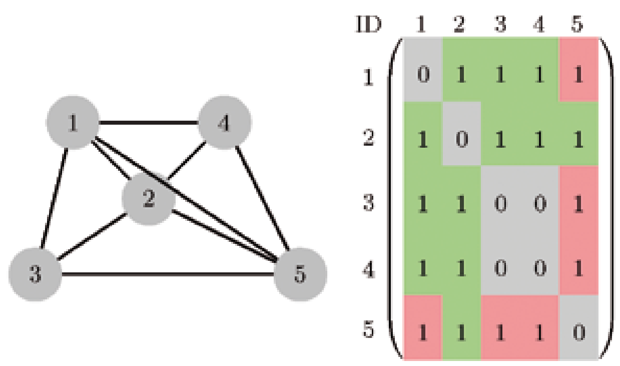
The routing is based on a proactive process, which consists of two main phases and several intermediate phases (**Figure 2**). At the beginning of each cycle the network discovery takes part (1), wherein the topology of the network is determined.
The network exploration messages contain data gathered from the network topology in the form of an adjacency matrix (**Figure 3**), and also information about the amount of GNSS raw data, that each participant will publish in the subsequent

Fig. 2



Principle of the time-synchronized communication

Fig. 3



Network topology and associated adjacency matrix

phase. Furthermore in the course of exploration the quality of the individual links is evaluated by the signal strength of the network and based on a threshold distinguished between stable and unstable connections (**Figure 3**, green: stable links, red: unstable links).

This increases the quality of the data exchange, especially in scenarios where the machines operate at the limit of stable connections to each other.

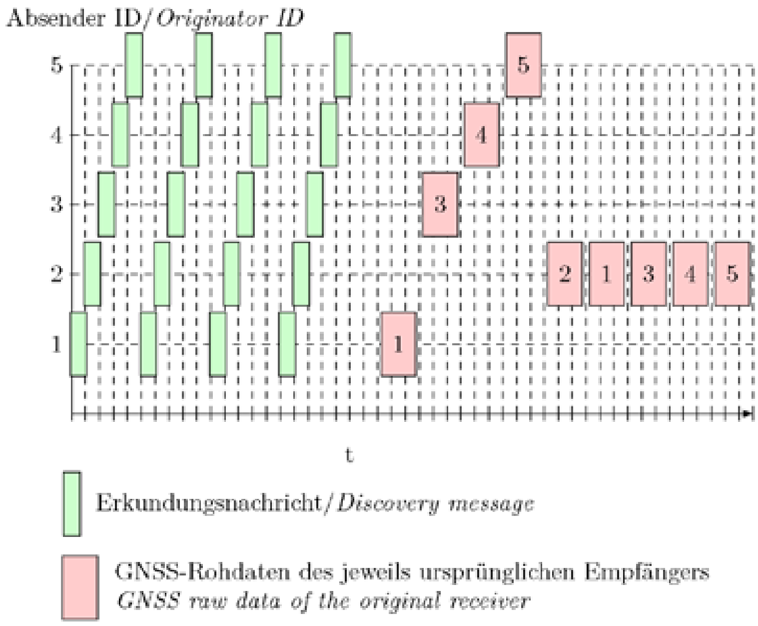
Figure 3 shows the data that is obtained in the form of an adjacency matrix for the example network. All collected information is then transmitted to the PC (2) in order to compute an optimal schedule for the data exchange. The result then is returned back to the microcontroller for further processing (3).

With the confirmation of this data (4) the available raw data for the next phase of exploration and exchange are transferred into the buffer (5). After a defined time, relative to the used trigger signal, the data transfer-phase (6) starts which is based on the calculated schedule, to ensure an optimal use of the transmission capacity. **Figure 4** shows the raw data packets received from four other participants before the own data is transmitted (from the perspective of node 2). After the data transfer phase the collected raw data is transmitted from the microcontroller to the PC (7) and the raw data for the next cycle is retrieved. Optionally, additional data, for example SBAS raw data is obtained from the PC (8) and confirmed (9) before the cycle starts again with the exploration of the network topology. Because the information about the amount of raw data which has to be exchanged must be available for the network exploration itself, this results in a temporal offset of one clock cycle, which is in this case a second. This is taken into account in processing the data for the position solution by corresponding filters (such as Kalman Filters).

Test Description

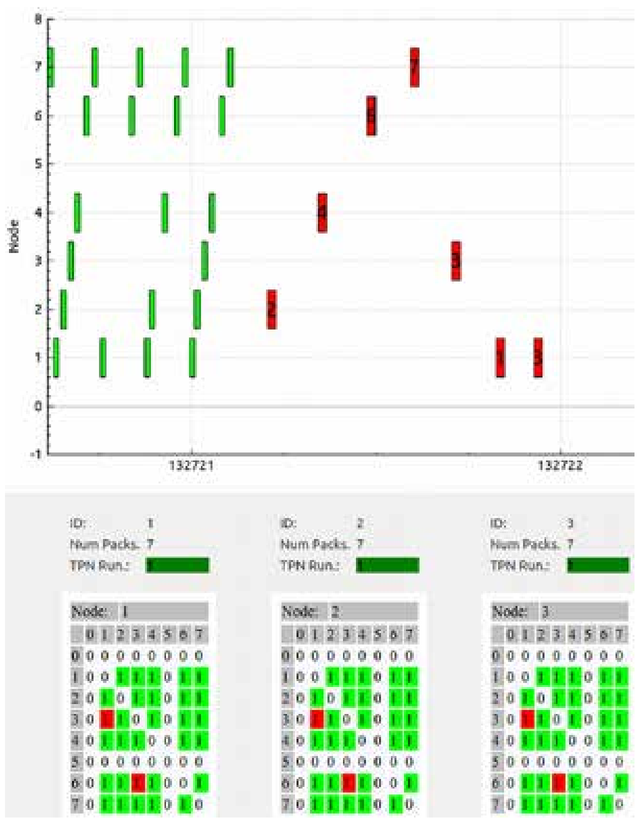
The system tests were performed both in an open area and in an urban environment. Different scenarios have been analyzed, such as a linear arrangement of the machines or a uniform distribution over the selected field. For visualization and analysis of message traffic on the network during the experiments a self-developed software is used. Therefore an additional passive communication device is integrated into the system, which receives all the available messages, so that any problems and faults can be analyzed already during the test. **Figure 5** shows a detail of the analyzed message traffic during a test. By the choice of public and freely usable frequency interferences from other devices such as remote controls from the modeling, from public WLAN, etc. are possible. In regard to the chosen approach of a time slot-based data exchange not successfully transferred data cannot be sent again under poor reception quality, since this requires a re-allocation of time slots for all participants. However, the reliability can be increased by favoring stable connections, while the signal strength for the connections between the participants for the GNSS raw data exchange is determined

Fig. 4



Example of messages during a cycle

Fig. 5



Extract from the network analysis of a running experiment

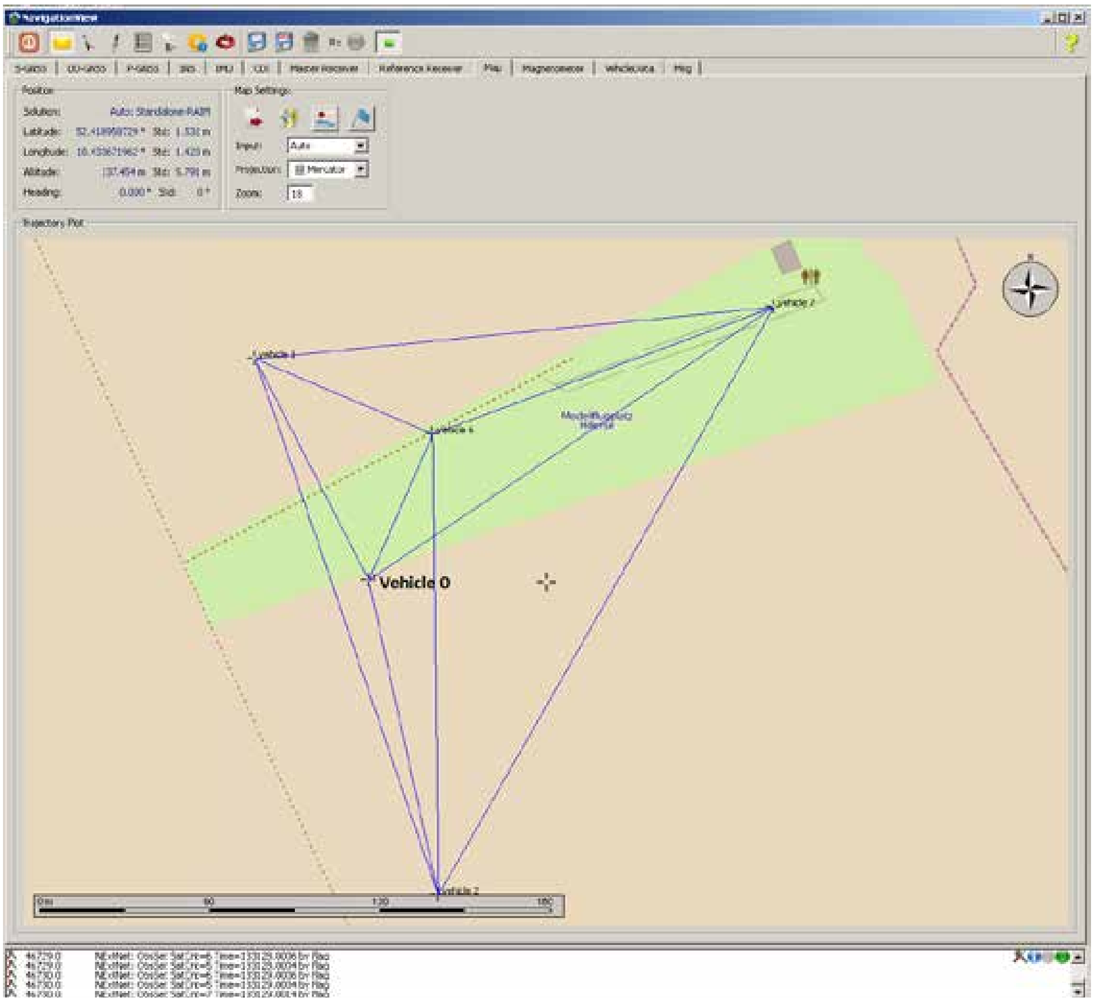
as already described and the usage of unstable connections is avoided if possible. This enables communication even under the influence of various interferences and insufficient reception conditions and results in successfully delivering a large part of the messages.

For a live visualization of the swarm positioning results a specific software tool developed at the IFF was used (**Figure 6**). For this purpose a data link via WLAN with one of the UAV or UGV of the swarm is established. Due to the fact that all exchanged data is available on each swarm participant and computed using the described cooperative approach, the position and baselines of all swarm participants can be requested using the WLAN data link and visualized within that graphical user interface. This way the operator gets an overview of the whole swarm and the common situation awareness, e.g. the spatial distribution of the swarm participants, can be improved. Within the visualization “Vehicle 0” denotes the UAV/UGV that is being used for getting the swarm positioning information. Further position information concerning this user is displayed on the top left of the GUI (Graphical User Interface). Because of the modular structure of the proprietary software developed by the IFF further information of the test carrier, e. g. a sky plot of the received GPS satellite, measurements and results of further sensors like the inertial measurement unit, can be displayed on other GUI pages (currently not shown in **Figure 6**).

Conclusions

Within real practical experiments the functionality of the GNSS raw data exchange was demonstrated, that is based on the

Fig. 6



Online presentation of the swarm positioning – positions and the UAV and UGV baselines

above described method and on the cooperative data analysis of all in the swarm exchanged data. The focus of the investigations was on the real-time data processing and the functionality in real-world scenarios, both in nearly undisturbed areas and in urban scenarios with strong restrictions on the GNSS quality and especially on the intra-swarm communication. Due to the complexity of the experimental setup and the large number of different and variable influences a quantitative statement regarding to the communication is difficult to determine. Qualitatively it can be said that the data exchange can be performed successfully and reproducibly even under difficult environmental conditions and widely varying topologies. Occasional loss of data in the form of missing messages occurs by not completely avoidable interference in the used free ISM band. A detection of missing data during the network exploration as well as during the raw data exchange is in principle feasible and was already implemented for testing investigations. However, a new request or a re-transmission of data packets is contrary to the generally approach. Due to the high repetition rate of the network exploration and the exchange of GNSS raw data, it is also more expedient to put the focus on the delivery of current information and not on a secured transmission of each data set.

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