AN EXAMPLE OF AN INTEGRATED GPS AND DR POSITIONING SYSTEM DESIGNED FOR ARCHEOLOGICAL PROSPECTING

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Abstract: Geophysical prospecting at archeological sites requires a flexible and relatively inexpensive positioning system, capable of determining positions within a circle with 30 cm error radius. GPS positioning technology is capable to achieve this accuracy only under favorable conditions, but can be supplemented, for more general use, with a dead reckoning (DR) MEMS accelerometer positioning system. In this contribution we describe such a hybrid GPS-DR system, developed for archeological applications, capable of reducing the trajectory orientation errors, which for the GPS alone can amount to ± 1 °, by 60 %. The improvement in the position data to the required precision in archeological fieldwork is demonstrated.

Primer integriranega lokacijskega sistema GPS in seštevne navigacije, namenjenega arheološkemu raziskovanju

Kjučne besede: seštevna navigacija, integrirana navigacija, geofizikalne raziskave, MEMS akcelormeter

Izvleček: Geofizikalne raziskave na arheoloških najdiščih zahtevajo prožen in relativno cenen sistem pozicioniranja, ki je spodoben določati položaj znotraj kroga napake s polmerom 30 cm. GPS navigacijska tehnologija je sposobna zagotoviti takšno natančnost le v ugodnih razmerah, ki jih pri terenskem delu običajno ni mogoče zagotoviti. Vendar pa se jo da z inercialnim navigacijskim sistemom, ki temelji na uporabi MEMS pospeškometrov, podpreti. V tem prispevku opisujemo hibriden sistem pozicioniranja, temelječ na GPS in seštevni navigaciji (dead reckoning – DR – navigacija), razvit za potrebe arheološke prospekcije, ki je sposoben zmanjšati orientacijsko napako GPS sistema (običajno v bližini ± 1 °) za 60 %. Pokažemo, da sistem lahko zagotovi pri arheološkem delu zahtevano natančnost.

1. Introduction

There is considerable commercial and research interest in a variety of applications for accurate location systems. Different systems are characterized by different levels of accuracy, coverage, cost of installation, operation and maintenance, frequency of location updates, etc /1/, /2/. Not surprisingly, in any application a system has its respective strengths and weaknesses. For example, a standard GPS-based system can achieve good levels of accuracy but in practice the coverage is often limited. GSM-based positioning has been advocated in various applications and claimed to achieve meaningful levels of accuracy at a very low cost, however not in the accuracy range of the GPS-based positioning /3/. It seems quite obvious that the choice of any particular location system for a specific application is highly application-specific. In this paper we consider a hybrid system for positioning in a challenging real world application: geophysical surveying of an archeological site. A typical application of the positioning system in an archeological prospecting setting is an amalgamation of position data with a ground penetrating radar, and/or ground conductivity or magnetic anomaly meters, etc /4/, /5/.

Geophysical measurements for extensive surveys at archaeologically unexplored sites, usually performed via common terrestrial geodetic procedures, can be considerably aided by the satellite navigation methods. The idea behind applying inexpensive, single frequency GPS systems to geophysical surveys in archaeological prospecting arises from their simple use, and the need for flexibility and effectiveness in such work. A sufficient degree of flexibility can only be assured by complete autonomy of the surveying team in the planning and execution of the fieldwork. GPS positioning technology is well suited for autonomous geophysical prospecting /5/, /6/, in particular in large-scale evaluation projects, where a comprehensive, detailed survey is not as important as establishing the background levels and acquiring a good understanding of the effects of the geology and pedology. Its efficient application is important for surveys in regions where geodetic fixed points for terrestrial position measurements are not accessible or available. In our previous work we have tested various types of inexpensive GPS receivers to asses the utility of the technique for archeo-geophysical surveying /5/, /7/, and demonstrated that it is possible to compensate for the errors, usually encountered in GPS positioning, to a considerable extend, and refine the results by post-processing of the measurement data. Under favorable conditions a 30 cm relative uncertainty of the kinematical positioning was achieved. This is considered sufficient in the type of surveying under discussion /8/.

It is characteristic of the GPS positioning methods that the accuracy of relative positions fixes is usually considerably better than the accuracy of absolute position fixes. However, with a comprehensive post-processing effort a very accurate static fix by single frequency GPS receiver is also possible /9/. We have attempted to improve the performance of relatively inexpensive GPS receivers by first establishing reference points of known position in the field. A roving receiver then continuously corrects its position outputs by calculating its pseudo range. This can be done relatively easily at a test site under favorable measuring conditions. However, an important practical distinction favors test sites from real life archeological sites in that at the later favorable conditions are seldom encountered. Therefore methods of augmenting a GPS system were sought. As in our previous work, we are concerned solely with horizontal positioning, which is of primary importance, leaving the more difficult problem of vertical positioning to a future project.

2. Hybrid GPS-MEMS accelerometer DR location system

Several methods of augmenting a GPS positioning system suggest themselves. It has been demonstrated /10/, that often a fusion of GPS and dead reckoning (DR), implemented e.g. by a compass and accelerometers, shows the best accuracy, significantly improving the accuracy of GPS alone. Such a fusion is by no means self evident, especially if relatively cheap and readily available micro machined MEMS accelerometers are used for augmenting the GPS system. There is a significant difficulty associated with the use of such MEMS sensors: their electrical parameters are not well defined and each manufactured device must be individually calibrated prior to use and relatively frequently recalibrated /11/. However, in this paper we attempt to demonstrate the viability and possibilities of a hybrid GPS-MEMS accelerometer DR location system for archeological prospecting fieldwork.

Despite a variety of detection schemes employed, every accelerometer can be modeled as a simple mass-spring-damper system, where the mass on the spring changes its position relative to its supporting frame with the input acceleration, forming a second-order system:

$$m\ddot{x} + c\dot{x} + kx = ma_{input}$$

where x is the displacement of the "proof" mass m of the accelerometer with respect to its frame, a_{input} is the external (input) acceleration, k is the suspension coefficient, and c is the damping coefficient of the system /12/. Determination of the displacement of the device along a trajectory with time proceeds by numerical integration of the input acceleration. Due to small errors of various sources in the accelerometer, integrator circuitry etc, long time integration results in an accumulation of errors and double integration compounds the errors ($\sim t^2$). Without frequent resetting of the measured position of the device to the actual position, huge errors can result. On the other hand, integration over short periods of time (in the order of 1 minute or less) can give satisfactory results, making supplementation of temporarily unavailable GPS signals with DR position data possible, or a correction of them, if the source of the GPS error can be detected. One such known source of GPS errors that can be corrected in a kinematical setting with a DR procedure is the error, due to the time delay between the actual position and the position indicated by the GPS system after the measurement and computation. The correction procedure implies a time triggered data acquisition procedure for both parts of the hybrid positioning system. The fusion of the DR and GPS is able to reduce the average GPS error by approximately 50% /10/ in a general setting and has been reported to reduce the maximum error by 70 % in favorable circumstances. It is perhaps remarkable, that integration of more than two positioning systems into one usually does not result in any further improvement of the accuracy /10/.

Due to the nature of the application of the hybrid positioning system being considered in our investigation, i.e. geophysical surveying of an archeological site, the system needs to be as simple as possible. It is basically comprised of 3 sensors: a GPS receiver and two MEMS accelerometers, augmented by a magnetic compass. The later serves principally as an orientation sensor, which is needed as an accelerometer by itself does not differentiate between a dynamic and the gravitational accelerations. In principle the data from the GPS receiver alone could be used to derive the required device orientation, eliminating the need for a compass. In practice, however, this proved to be unreliable. On the other hand, orientation data from 2 GPS receivers proved sufficiently accurate and reliable for the purposes of the proposed application. In this case a second GPS receiver replaces the compass, resulting in a hybrid system that has proved itself to be even easier to manage than the one with a compass. The practical difference between the two is basically due to different and incommensurable sampling rates from the GPS receiver and the compass, often causing timing errors. We need to stress again that system devised is tailored to a particular application and is therefore perhaps no suited or optimal in other applications.

The hybrid location system we have developed consists of a GPS receiver (FlexPak, NovAtel) with choke-ring antenna, two perpendicularly mounted two-dimensional MEMS accelerometers (ADIS16201, Analog Devices) and a magnetic compass (HMR3300, Honeywell). Sensors are driven by a microcontroller A T90S4433 (Atmel), and their data transferred to a personal computer, used for the data processing, via two ISM radio band links (ER 400TRS, Low Power Radio Solutions). During use of the system the GPS position data are combined and corrected with the acceleration data by the standard DSP techniques /13/. Walking speeds attainable by a prospector in a field rarely exceed 1 m/s, and his kinematical position (actually, the position of the device he carries or drags behind him) can thus be deduced from accelerometer data sampled below 10Hz. A synchronization of various positioning device outputs of the hybrid system involves a matching algorithm which takes typical delay times in consideration. An effective coupling of the DR data with the GPS data is then achieved by Kalman filtering. The scheme of the system is shown on Fig. 1 and the system itself in Fig 2. Fig. 3 illustrates the whole positioning system, mounted on a carrier together with a ground penetrating radar, in use.

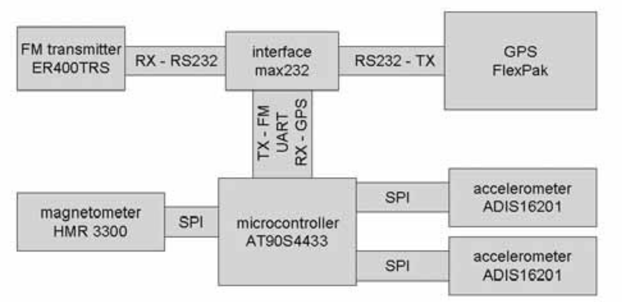

Fig. 1. A block diagram of the GPS/MEMS dead reckoning (DR) hybrid device.

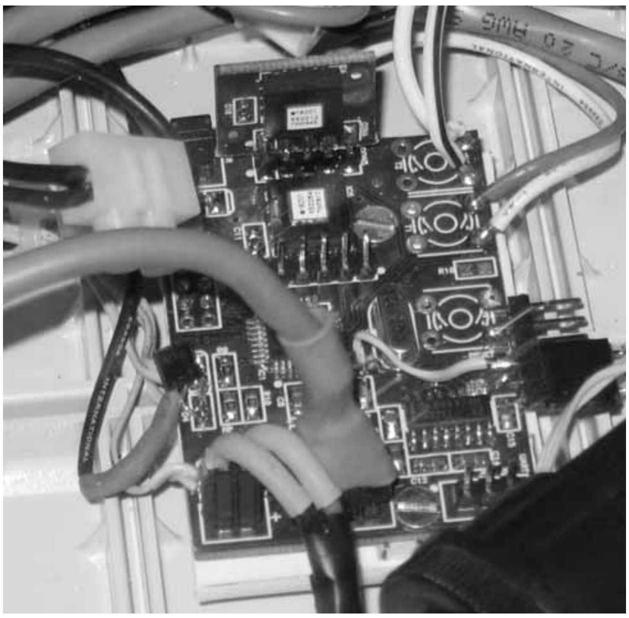

Fig. 2. A detail of the hybrid system: the two perpendicularly mounted MEMS chips with the controller board. Due to the interferences caused by the GPS receiver, the magnetometer unit is placed separately.

Fig. 3. Ground Penetrating Radar (GPR), the position of which is recorded by the proposed hybrid positioning system, comprising a GPS receiver SR 20, georeferenced by GS 20 (Leica), and the dead reckoning (DR) accelerometer subsystem, in use at an archeological site. Both positioning devices are placed at the top of the GPR antenna.

3. Results and discussion

The starting point of the present investigation is the result, established in our previous work /14/, that a GPS positioning system is not perfectly capable of assuring the required accuracy of 30 cm in all circumstances. The absolute distances between two locations in a field, as measured with such a system, are generally compatible with the required precision, but the orientation of the measured trajectory of the surveyor in the field is not. Even in favorable conditions the orientation of a measured straight trajectory deviates from the actual trajectory of a surveyor by ± 1 °, resulting in a positioning error that exceeds the required accuracy after only 17 m displacement along a straight trajectory. To a certain degree this can be compensated for by frequent referral to the established reference points in the field and/or corrected by the calibrated DR acceleration data.

Calibration of the DR sub-system of the integrated positioning device has been preformed along a 15 m straight track, measured with a laser measuring device, with well defined starting and end points. The instrument, positioned on a sledge, was dragged along the chosen path at a typical rate of somewhat under 1 m/s, and 60 runs were performed in several sessions on different days. Fig.4 represents a typical run along the test track. The waviness of the trajectory in an illustration of the fact, that for a human operator, dragging the sledge with the measuring equipment behind him, it is considerably easier to aim for the final position than to accurately follow a predetermined path, even if this is straight. The final position data were analyzed according to standard procedures /15/ and compared to the actual position of the end point. The measurements from a single session comprise a cluster of data form which the average final position for that session is calculated. This position varies between different sessions, with a compound rms final position error for all clusters together being 25 cm, which corresponds to a ± 0.95 ° direction error. This is comparable to the direction error of the GPS measurements alone. However, separately considering only clustered data from a single session, the results show a considerably more favorable picture. The rms error of a cluster of data is 15 cm in the longitudinal direction, and 11 cm in the transverse direction. We attribute this difference to the fact that the disturbing forces during a run act primarily parallel to the path taken, with the transverse disturbances being considerably smaller. The direction accuracy, which is of primary concern to us, depends only upon the scatter of the data in the transverse direction and the stated rms in this direction represents an angular error of only 0.40 °, an improvement of 60 % relative to the GPS positioning. This is entirely within the range of reported performances of similar systems in different applications /10/. By combining the absolute displacement data, as measured by the GPS subsystem, with DR direction data, our hybrid system is thus capable of assuring the accuracy of positioning as required by the archeological field work.

The origins of clustering of the accelerometer position data between sessions are not understood at this time. In the field work it would be of considerable practical importance to eliminate the clustering. On the other hand, to large extend the question can be avoided by a resetting of the DR subsystem at the end point of the test track or, in the field, at the previously established reference points. The overall reliability and robustness of the DR subsystem is demonstrated by the fact that, regardless of the clustering, the average of the absolute distances traveled by the device over all sessions, as measured by the DR method, is within 1 cm of the actual distance between the starting an end points of the 15 m test track. Thus we conclude that the scatter of the final position data is caused by random and not systematic errors.

The determination of the actual trajectory taken by the surveyor in the field proceeds by measuring the staring and end points of segments of the trajectory taken. Starting form a known position, the pseudo position of the end point of each approximately 10 – 15 m long segment is first determined from the GPS data, and then corrected by the DR direction data. This position is then taken as the starting point of the next segment and its endpoint determined in the same manner. From the known positions of the starting and end points of a segment, the actual position of a point on a segment can then be determined by the standard interpolation of its pseudo position. The segmentation of the trajectory thus takes advantage of the relatively accurate absolute distance data offered by the GPS part of the hybrid system, and the relatively accurate direction data of the DR subsystem, whose limited range is not exceeded by the segment length. A successful implementation of the proposed GPS and MEMS DR sensors fusion in realistic surveying conditions is significantly augmented by an appropriate analytical model of the data acquisition and manipulation process. The model is tuned by fitting its outputs to the positions of the established reference points, and a correspondence between the hybrid system outputs and the subsequent DSP processing is thus established. The model is still being improved, but its original version and the described hybrid positioning system have been extensively tested and used at Tanagra, a large and unexplored archeological site in Greece. The data obtained there are still being evaluated and results will be reported elsewhere.

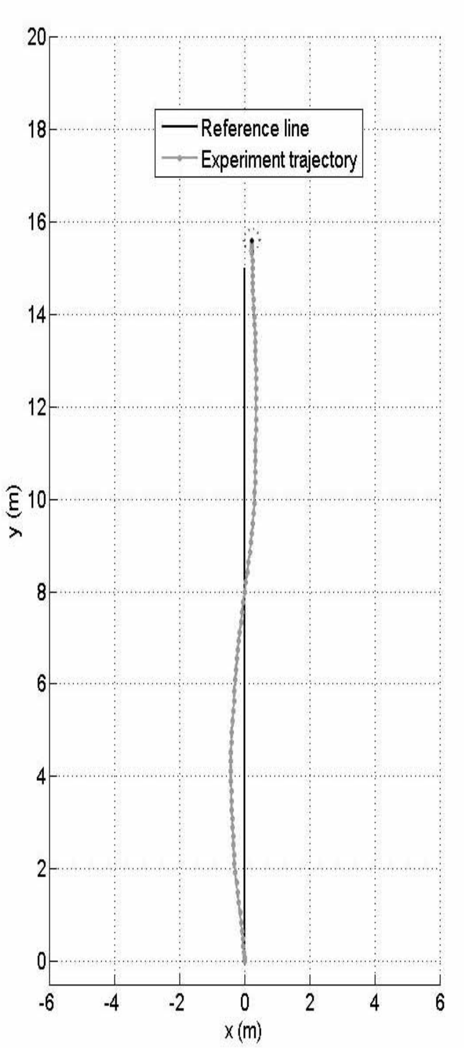

Fig.4. A typical run along the test track. The waviness of the trajectory illustrates the difficulty of dragging the sledge with the measuring equipment along a predetermined path. For a human operator it is considerably easier to aim for the final position, compensating for digressions, which results in a wavy trajectory.

A completely different approach to accurate positioning with the same hybrid system as described above is suggested by Cho and Park /16/: the change in position of a surveyor is calculated by the estimated average length of his step, the number of steps he takes, and their directions. Correct step length estimate is crucial for the success of the method. The acceleration signal pattern from the MEMS sensors is used to count the steps. However, the unavoidable misalignments of the device are a source of serious errors, and the magnetic compass azimuth data must be used in the tilt compensation algorithm. With this approach we have been unable to reproduce or even approach the precision of the hybrid system, described above, even on a level, smooth test-field, and at limited displacements. Thus the validity of such an approach in a more general situation is questionable.

4. Conclusion

Geophysical prospecting at archeological sites requires a flexible and relatively inexpensive positioning system, capable of determining the positions of test equipment within a circle with 30 cm error radius. As the GPS positioning technology is capable of achieving this accuracy only under favorable conditions, seldom encountered in fieldwork, we have developed a hybrid positioning system, comprising of a GPS receiver and (DR) MEMS accelerometers, which is capable of augmenting the GPR positioning data. The described system is capable of reducing the GPS trajectory orientation errors, which usually amount to ± 1 °, by 60 %, thus assuring the required accuracy. We report on the calibration of the system in test surroundings, while and extensive survey of an actual archeological site, which has been performed with the system, is still being evaluated and will be reported at a later date.

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