Mapping, SLAM

Auditorium D8

Wednesday, September 15, 16:00 – 18:00
Simultaneous Mobile Robot and Radio Node Localization in Wireless Sensor Networks

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1 Summary

Accurate and cost effective localization is a basic issue in the field of mobile robotics. This work shows how it can be solved by using wireless radio nodes as landmarks. Mechanical scanning is employed at the mobile robot to measure the angle of arrival of radio signals. A measurement integrity check is realized by means of normalized cross correlation. This enables the recognition of multi path propagation and radio interferers, thereby ensuring high robustness. A simultaneous localization and mapping approach is implemented to localize the robot and to build a map of static radio nodes simultaneously. This allows localizing the robot in unknown environments in an ad hoc and unobtrusive fashion.

2 Method to measure the angle of arrival

The foundation of this work is a new method to measure the angle of arrival in wireless networks based on the received signal strength indicator (RSSI). It requires the antenna on the robot to be rotated about a vertical axis while recording the RSSI. This results in a radiation pattern in the azimuth plane. Its cross correlation with the known reference radiation pattern of the antenna allows to determine the relative angle. A detailed description of the method and a thorough error analysis are given in [1] and [2]. A schematic of the setup is shown in figure 1. To ensure a distinct radiation pattern, a monopole antenna is slightly modified by the attachment of a reflector plate. This increases the uniqueness of the angle given by the cross correlation. The advantages of this method are its robustness to antenna anisotropy of the static nodes and the possibility for measurement integrity by the consideration of the maximum correlation coefficient, which is a measure for the similarity between the recorded and the reference radiation patterns. Thereby the localization is robust in multipath environments. Further the presented method does not require any modification of the sensor network and thus allows the use of commodity radio hardware. It also does not assume any propagation models and therefore does not require any parameters to be known in advance enabling localization in completely unknown environments.

![Figure 19: Setup for the determination of the relative angle: $\phi_a$ is the rotation angle of the antenna, $\phi_r$ is the relative angle to the static node with position $x_n$.](image-url)
3 SLAM

Based on this measurement method we apply the SLAM approach to simultaneously localize the robot and the radio nodes. Therefore Bayesian filtering is employed that incorporates the odometry of the robot using a motion model. To localize the robot and the nodes an Extended Kalman Filter (EKF) is used. Since only the angle of arrival is available and the measurement model is not linear, a particle filter is used to initialize the location of the static nodes. Once the uncertainty of the particle filter falls below a certain threshold a new node is inserted into the EKF where its location is further tracked and where it simultaneously serves as an anchor node to localize the robot.

We have carried out experiments in outdoor and indoor environments. An optical tracking system is used to determine the ground truth position of the robot indoors and a real time kinematic GPS outdoors. A sample run is shown in Figure 20. A comparison with our localization method shows a mean error for the position of the robot below 10cm in both environments. Based on the outdoor experiments we show the contribution of the RSSI based localization by implementing batch processing global optimization to determine the location of the nodes and the robot without odometry, similar to bundle adjustment. The experimental results show, that odometry and a motion model are accurate on a short distance and are thus useful to detect outliers. Complementary to this our method for RSSI based localization gives an accurate absolute reference.

![Figure 20: Results of an exemplary run in an office environment: The robot travels between tables and cupboards (indicated by the grey rectangles). Line-of-sight is not given in most cases. The estimated path of the robot is shown by the green line. The estimated node position is shown by the green crosses. Its uncertainty is indicated by the blue ellipses.](image)

References


1 Summary

We present the map modelling toolkit YAMAMOTO, which allows to efficiently model and design assistive building environments in 3-D. We focus on the tool’s ability to represent and simulate sensors and actuators, i.e. navigational beacons used for indoor positioning and navigation purposes. An interactive avatar can be used to simulate and evaluate location-based applications in the virtual model. Vice versa, the model can be used to visualize the state of the real world, including the location of the user and the content of public displays.

2 Modeling the Building Structure in 3-D with the YAMAMOTO Toolkit

In this paper, we present the YAMAMOTO (Yet Another MAP MOdeling TOOLkit) toolkit for the modelling, designing, and simulation of assistive environments. Application domains comprise pedestrian navigation, home automation, and ambient assisted living. The typical workflow to create a building model with YAMAMOTO is to use a floor plan as backdrop image and to trace the outlines of rooms and corridors in 2.5-D as spatial regions that are represented by vertices and edges. Optionally, polygon data can be imported from CAD systems. The spatial regions should partition the space, so that each coordinate can be mapped to exactly one region, i.e. to query the room in which the user is currently located. Multiple levels can be represented as horizontal planes that are arranged along the z-axis in 3-D space. Although the spatial regions are represented as “flat” objects, they can be visualized from an egocentric (avatar) perspective in full 3-D using parametric objects; based on semantic annotation of regions and edges with information about type and passableness, parametric objects automatically generate the geometry for walls and doors, as shown in Figure 1.
In order to represent the rooms' furnishing, further 3-D objects can be used to model shelves, cabinets, and tables, which are specified by their type and dimension. All regions and objects can be labelled with symbolic identifiers to refer to an external database or ontology.

3 Modelling Instrumented Environments with Sensors and Actuators

Indoor positioning requires an arrangement of sensors and actuators to measure distances (signal strength or time of flight) or angles in order to estimate the location of the user by trilateration or triangulation. Therefore the location of the devices must be known to the positioning system. Figure 1 shows the instrumentation of our lab with RFID and IR beacons, which are received by a mobile terminal that computes its position based on the known position of the beacons (Schwartz et al., 2010). The YAMAMOTO toolkit further allows to geo-reference the model according to known points or aerial photographs (by manual alignment), so that local (model) coordinates can be converted to geographic (Longitude/Latitude) coordinates for a seamless transition between indoor and outdoor (GPS) positioning systems. Modelling buildings in 3-D allows to visually identify obstacles between sender and receiver units, and to represent geometrically challenging situations, such as staircases. Modelling the interior of buildings on a high level of detail further helps the designer to plan the coverage and precision of the positioning infrastructure according to the users’ activities.

4 Navigational Aid for Pedestrians

Seamless route-finding is supported in indoor and outdoor environments without the need for explicit modelling of path networks. The YAMAMOTO toolkit includes the PATHFINDER component that has been implemented to find shortest paths in multi-level building models. The semantic annotation of edges (doors or walls) allows the algorithm to perform an A* search directly on the spatial regions. Figure 2 shows an example route from the first- to ground floor.

5 Simulation and Evaluation of Assistive Environments in VR

The toolkit provides an interface to get and set the state of all modelled objects through external programs, hence it is possible to visualize the measured position of the user by the avatar in the virtual model. Vice versa, the avatar can be controlled by the user to simulate a precise indoor positioning system in VR to evaluate location-based applications. The virtual display objects implement a video streaming client (VNC) so that any content from an external application can be shown in real-time in the 3-D world. Our kiosk-based pedestrian navigation system VISTO recognizes users via mobile Bluetooth devices. For the simulation, we implemented virtual proximity sensors; as the avatar enters their range, they send the user’s ID to the application and user-adapted output is streamed from real to virtual displays.

6 Conclusions and Outlook

YAMAMOTO has been designed as an easy to learn and efficient modelling toolkit for buildings. Semantic annotation allows for the automated generation of 3-D geometry and route finding. The tool also supports the simulation of assistive environments, i.e. for indoor positioning applications and navigation. For the future, a physical simulation of radio signals, considering obstacles and materials, would be of interest for the planning of positioning systems.

Automated Localization of a Laser Scanner in Indoor Environments Using Planar Objects

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1 Summary

A method is presented for automated localization of a laser scanner in an indoor environment. Planar features extracted from the range data undergo a linear plane matching model to estimate the relative scanner positions in consecutive scans. The performance of the method is demonstrated using a dataset of six panoramic scans of an interior, and the accuracy evaluation of the computed positions indicates localization errors of a few centimetres.

2 Introduction

A new trend in terrestrial laser scanning is the development of an autonomous system that is able to scan an indoor environment from a number of predefined positions, register the scans, and provide an accurate and complete point cloud of the scene. Such a system would require the automation of two main processes: scanner localization and the registration of the scans. In theory, automated registration precedes the localization problem, because a correct registration of consecutive scans provides the relative position and orientation of the scanner in every pair of scans. In practice, however, existing registration methods are slow and iterative, and require an approximate estimate of the transformation between the two scans. Alternatively, if the motion of the scanner from one scan position to another can be estimated from the data, it can serve as an initial approximation to perform an iterative fine registration of the scans, which will in turn lead to an improved accuracy for the localization of the scanner. In this paper, we describe a new method for the localization of the laser scanner using planar objects. The method is based on inferring a transformation from a set of corresponding plane-pairs within a linear least-squares plane matching model. The benefit of the linear estimation model is that it requires no initial approximations, and leads to a more efficient search for correspondences. The correspondence problem is approached with an initiate-and-extend search strategy, which begins with initial correspondence hypotheses and extends the correspondences when more plane pairs fit into the estimated transformation.

3 Overview of the method

The underlying principle in the plane matching model is that given a minimum of three plane correspondences in two scans (subject to the condition that the planes intersect in a point), a similarity transformation between the scans can be estimated such that the norm distance and difference in the direction of normals between the planes is minimized. Formally, the plane matching equation is expressed as: \(
π^1_j = H^{-1}π^2_j
\) where \(π^1_j\) and \(π^2_j\) are planes in the two scans, and \(H\) is a transformation between the scans. Given a number of corresponding plane-pairs, the plane matching equation is rearranged to form a system of linear equations wherein \(H\) is estimated in a least-squares fashion.
To establish correspondence between the planes, we perform an initiate-and-extend search strategy, which works in two steps. In the first step, initial combinations of three or four plane pairs are created using a small subset of the planes in each scan. At this stage, loose constraints are imposed to reduce the number of initial combinations while maintaining the correct correspondences. A transformation is estimated for each initial combination. In the second step, each initial combination is extended with new planes in the two scans that fit into the estimated transformation. Extending the initial combinations provides a straightforward method for finding the correct transformation by picking the largest extended match set (the winning match set).

4 Experimental results

The performance of the plane matching method was evaluated using two indoor datasets. Figure 1 shows the reflectance image pertaining to one scan in the first dataset. This dataset consisted of six panoramic scans of an anterior of about 8 x 25 x 3 meters dimension. The position of the scanner at each scan was measured by a total-station to serve as reference in evaluating the localization results. Planar segments were extracted from each scan using a segmentation algorithm, and plane parameters were obtained by performing a least-squares fitting procedure. The plane matching process was performed with planes in all six scans in a pair-wise fashion, and the position of the scanner at each scan was computed. Figure 2 shows the computed scanner positions together with the reference measurements. The closing error shown in the magnified box represents the accumulated error of localization in six scans. The closing error was found to be 2.7 cm, while the RMS error of the computed positions amounted in 6.0 cm.

5 Concluding remarks

We introduced a plane matching method for the localization of a laser scanner in an indoor environment. The method is shown to perform robustly and reach localization accuracies in the order of centimetres. A main requirement of the method to yield a unique localization solution is the availability of a minimum of three planes (in each scan) that intersect in a point. A possible degenerate configuration of the planes is one with only walls in the scans, which cannot constrain the motion of the scanner in vertical direction. Such a constraint can be provided by including the planes of the floor or the ceiling in the plane matching estimation model.
UWB SLAM with Rao-Blackwellized Monte Carlo Data Association

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1 Introduction

The scenario envisioned in this work is an emergency, where a building is filled with dust and smoke. A robot should build a map of a building and locate itself on it (simultaneous localization and mapping, SLAM). In this scenario, conventional means of navigation, i.e. optical systems, do not work. A bat-type UWB radar array, i.e. two RX antennas and one TX antenna in the middle, is suitable for this task. The main challenge is data association, the task of assigning measurements to corresponding landmarks. A solution is presented in this article using a Rao-Blackwellized particle filter.

2 Related Works

The great advantage of the bat-type UWB radar is the fact that it works without a priori knowledge of the surroundings and without any kind of infrastructure. This sets it apart from other means of indoor navigation, for example based on WLAN or RFID. Although those systems do not have to cope with data association, they are often not suitable for an emergency scenario as they need infrastructure. UWB is also a good choice for this task as it can provide additional information like life signs of humans, material characteristics, or even information about objects inside or behind walls. This work builds upon previously published results that also deal with the bat-type sensor array.

3 Overview

The bat-type configuration consists of an antenna array with one transmitter in the middle and two receivers to the left and right. An M-sequence UWB radar is used to measure impulse responses of the surroundings. By evaluating the peaks in the time-of-flight measurements at different positions, it is possible to deduce the location of features like walls, corners or point scatterers. Those features are used as landmarks for navigation and build a feature-based map of the building. They are tracked using a state-space model and an Extended Kalman Filter (EKF) to estimate their positions. The state vector $x$ comprises of the robot pose and the landmark positions in two dimensions:

$$\mathbf{x} = [x_{\text{robot}}, y_{\text{robot}}, \phi_{\text{robot}}, x_{\text{landmark 1}}, y_{\text{landmark 1}}, \ldots, x_{\text{landmark n}}, y_{\text{landmark n}}]^T$$

4 Data Association

For the Kalman Filter to work properly it must be known which measured time-of-flight belongs to which landmark. A basic method to accomplish data association is the Nearest Neighbor (NN) method. Here, we use the predicted measurements of the EKF. For all measurements $z_i$, we calculate the measurement probability

$$p(z_i|x_i^r, c_i=j)$$
for all landmarks j, where \( c_i \) is the correlation variable that stores which landmark is the assumed source of the measurement. The landmark with the highest probability is then associated with the measurement. This method works reasonably well for conditions with low noise, good position estimates and no false measurements. However, these preconditions do not always hold. For enhanced data association, we have to look not at a single, but at multiple hypotheses. One mean to do so is to use the Monte-Carlo-method also known as particle filter. In our case, we use the particle filter only for data association. Estimates of the state are calculated using Kalman Filters. The resulting filter is known as Rao-Blackwellized Particle Filter (RBPF). Each particle \( p^{(l)} \) comprises the state estimation \( x^{(l)} \) and the error covariance matrix \( P^{(l)} \), both used in the EKF. The correlation vector \( c^{(l)} \) contains the actual data association, and the weight \( w^{(l)} \) quantifies how good the hypothesis matches the reality of the measurements:

\[
p^{(l)} = [x^{(l)}, P^{(l)}, c^{(l)}, w^{(l)}]^T
\]

In each step, for every particle the following quantities are computed: The new state estimate and the estimated measurements are calculated based on the old one using the basic EKF equations. Then, for all measurements \( z \) an importance distribution \( \pi_j^{(l)} = p(z|x^k, c = j) p(c = j) \) is calculated and normalized. From this probability distribution the data association is drawn by Monte Carlo methods. With this data association, the state is updated and the new weight \( w_k = w_{k-1} p(z|x^k, c) \) is calculated. This is done for every particle. Resampling occurs if the number of effective particles falls below a threshold.

5 Results

First results are shown in Figure 1 (left). Shown is the percentage of correctly reconstructed rooms for a simulated test scenario plotted against position uncertainty. The RBPF (solid line) with 100 particles is significantly better than the NN (dotted line). In Figure 1 (right), every 10\(^{th}\) measurement is replaced by a false measurement, which still leads to acceptable results.

![Figure 1: Percentage of correctly reconstructed rooms for RBPF and NN. Left: no false measurements. Right: 10% false measurements](image)

6 Conclusions

The RBPF proved to be an appropriate tool for accomplishing the task of data association. Although it requires more computational power than the simpler Nearest Neighbor (NN) algorithm, it is still fast enough to allow for real-time applications. It is better than the NN in terms of reconstruction quality, and has a better ability to cope with false measurements.
Developing an Integrated Software Environment for Mobile Robot Navigation and Control

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1 Summary
A flexible modular robotic software environment based on the popular MRPT toolkit is reported in this paper that is able to easily integrate path planning, navigation and control algorithms from several sources. The different modules (responsible for SLAM, trajectory tracking, sensor and actuator handling, visualization etc.) communicate with each other via a carefully developed network based protocol set that ensures transparency and robust operation. The system can also be used as a simulation environment and it is capable for the comparative benchmarking of different navigation algorithms. The laser scanner based map building and navigation of an autonomous wheelchair is shown as an application example to illustrate the features of the developed software environment.

2 Motivation and aims
Currently, there have been numerous navigation and control algorithms and techniques in the field of indoor mobile robotics. Available robotic software toolkits present several implemented algorithms, but system-level integration still remains a challenging task. This inspired us to create a high-level, modular robotic software environment based on a selected toolkit to handle our special application requirements and significantly extend previous functionality. Beyond the standard requirements for a robotic software environment such as robustness and portability, our high-level, integrated system was designed to meet the following main requirements: a) strongly modular construction, b) multi-host, distributed architecture, c) probabilistic computational framework, d) such an environment where the incorporation of new algorithms and features is easy.

3 Basic tools
Our system is based on Mobile Robotic Programming Toolkit (MRPT) [1]. MRPT was selected because this framework uses a coherent probabilistic approach that is very useful in solving indoor navigation tasks. Furthermore, it contains a large amount of algorithms and software tools like SLAM techniques [2], Kalman Filter, Particle Filter, hardware drivers, data structures for several kinds of maps, visualization, and many auxiliary utilities. Using the algorithms implemented in MRPT, a set of separate modules were created using codes also from external sources or from our own implementations.

4 Design principles and properties of the modular system
Each module is responsible for a specific task like SLAM, path planning, trajectory following control, handling of sensors and actuators, and visualization. Apart from the above tasks, additional modules were implemented that allow us to use the system as a simulation environment, too. Such modules are responsible for recording the measured data and playing it back, and for monitoring the inner state variables of the system. The architecture
provides transparency between the real and simulated experiments. Running different algorithms simultaneously on the same data can also be done, thus comparative benchmarking is possible. Extending this system by adding new modules is quite easy. Using the module’s connection interface provided by our framework, the algorithm running in the heart of the module obtains all data to process. There is no need for further modifications in the algorithm as only the incoming and generated data structures should be adjusted to the other module’s data representation. Separating the system’s functionalities into modules ensures robustness and safety: if a single module fails, it will not cause the whole system’s failure generally, since other independent modules can work properly. The unified form of data representation used at the communication allows us to change specific modules without modifying any settings or parameters in other modules. This unification was solved by the MRPT built-in object serialization.

The modules communicate with each other via a well-defined interface and protocol set, while performing their tasks. The communication protocol defines message types containing specific data (e.g. robot position, planned path, motion command, etc.). The transport is solved by using the standard TCP/IP protocol, while the distribution of messages is handled by a central module using publish-subscribe based architecture. The network handling layer is completely transparent for each module, which means that the modules have (and need) no knowledge about the specific data sources.

5 Application example

Our long-term project is to develop an autonomous wheelchair for handicapped schoolchildren. The reported robotic software environment was developed partially for this indoor mobile robotic task. Our project’s testbed was a PowerBot robot equipped with a SICK LMS100 laser range finder. With the help of our system, we were able to investigate several algorithms’ attributes: regarding the SLAM, we compared scan matching based algorithms, i.e. the classical Iterative Closest Point (ICP) registration algorithm [3] to the ICP with Levenberg-Marquardt optimization [4]. In the field of path planning, we compared A* and D* Lite algorithms. The current capabilities of the software system enable the robot to perform autonomous navigation in indoor environment including SLAM, planning and execution. For the illustration of application possibilities, Figure 1 shows integrated visualization in operation where several modules’ output can be seen, e.g. SLAM, path planning.

References

1 Summary

This extended abstract presents a doctoral project in its initial phase. The objective is to implement a precise localization and mapping system that is able to track a pedestrian in known and unknown environments. To achieve this, the well-known SLAM (Simultaneous Localization and Mapping) method will be applied that is already used for mobile robots. The pedestrian will be equipped with a short-range laser scanner, an inertial measurement unit (IMU), and a wearable computer for processing purposes. To obtain localization, the sensor data will be fused and processed with an algorithm based on the Extended Kalman Filter and Rao-Blackwellized Particle Filters. Mapping will be achieved with grid mapping.

2 Introduction

Localization and tracking of persons, agents, objects, etc. has been the object of significant studies among research groups over the last years. The pursuit of knowing the position of an agent, and even tracking it, is of crucial importance in many applications. Localization can be divided into two different scenarios: outdoor and indoor. These scenarios are addressed in different ways, and are solved through diverse methods and implementations. Outdoor localization methods can be obtained with GPS, field strength measurements (WLAN, GSM, Bluetooth), etc. For a precise indoor localization GPS cannot be used due to attenuation and scattering of the signals [1]. Preferred methods for indoor localization are the utilization of pre-installed indoor communication infrastructures, laser, radar, sonar, camera, motion sensors, etc. Assuming that not all buildings have a pre-installed communication infrastructure, the field strength measurements methods also cannot be used. For a precise indoor independent localization, it is important to perform sensor fusion with the above-mentioned methods [2].

3 SLAM

Simultaneous Localization and Mapping (SLAM) is a well-known solution in the area of mobile robotics. Many other approaches have been proposed for solving this particular problem. The most popular algorithms to solve the problem are based on the Extended Kalman Filter and the Rao-Blackwellized Particle Filters [3]. The problem has been solved in general, but it probably needs some algorithmic improvement.

This method basically works as follows: The mobile robot is equipped with a laser scanner, mounted on top of it, to take horizontal measurements. With this laser it is possible to take measurements of different landmarks, obtaining distances and angles. Landmarks are basically features in an environment that can be used as reference and for the registration of multiple scans when combining different measurements from diverse positions. For example,
in an indoor environment, landmarks could be lines, walls, corners, edges or more specific obstacles. The data obtained from the laser are fused with the mobile robots odometry; using the proposed algorithms it is possible to establish an approximation of the robot position at all times. At the same time a 2D map is constructed of the environment.

4 Indoor Pedestrian SLAM

The implementation of SLAM for pedestrians is based on [2] for this project. For pedestrians, the SLAM problem must be addressed in a different manner, due to the different movement conditions. Pedestrians have a much more complex odometry than mobile robots: they differ in the type of movements and degrees of freedom. The laser scanner position with mobile robots is stable compared to the surface. This cannot be guaranteed for human beings. Furthermore, the human body is specific to each person, as is motion. Thus, the challenge is to extract the odometry for each pedestrian and to obtain stable laser scanner data.

In this project, the pedestrian will be equipped with a short-range scanner and an Inertial Measurement Sensor (IMU). Positioning of the sensors is crucial to noise reduction and/or incorrect measurements. In mobile robots, the laser scanner is implemented on top of it and is able to scan a horizontal plane. The most stable positions on the human body to place the sensors are the shoulders and hips. To obtain horizontal laser scans, the raw data requires processing with the IMU data and projection onto the horizontal plane. Additionally, to reduce false laser scan readings, the scanner will be regulated with an electro-mechanic stabilizer so its measurements are always taken horizontally.

To extract odometry from the pedestrian, the data from the Inertial Measurement Unit will be processed to obtain step length and direction. Thus, by combining pedestrian odometry, laser scanner data, and using an Extended Kalman Filter or the Rao-Blackwellized Particle Filters, it is possible to achieve a precise localization.

The mapping can be accomplished by using a grid mapping method. This basically works by dividing the environment into small grids, and deciding whether that grid is occupied or not by scanning the environment. If a grid is occupied, then the system assumes that there is a solid object there; so it is drawn in the map.

Data processing will be accomplished with wearable computing devices, so there will be total independence of any main computer or network.

5 Conclusions

The proposed method is a different way to address localization of pedestrians. It is independent from the indoor environment; no a priori information is needed and it is comfortable to wear.

This tracking and mapping method is not meant to be used by any person, it is rather built for specific applications, where precise localization and mapping of a pedestrian is needed.

6 References

Creation of an Urban Spatial Model for In-City Positioning Using Laser-Scanning

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1. Summary
The investigations are based on the evaluation and the analyzes of high accuracy LIDAR images taken over Lithuanian cities, thereby taking into account the geodetic control measurements and foreign expert experience. The progressive aerial laser scanning approach with combination of digital photogrammetry technology, – a GPS-IMU system and a digital aerial photography have been used for the creation the urban spatial model. The application feasibility is investigated. A description of equipment, technological features and application possibilities is presented.

2. Technological features
Digital photogrammetry technology fused with laser scanning data is analyzed considering in-city location determination that can be used for indoor positioning, e.g., surveys of excavation, design of industrial equipments, reconstruction of architectural monuments, etc.
1. LIDAR images. This includes Lithuanian urban areas scanned by Geokosmos (Moscow) using scanner Optech ALTM 3100 from the airplane Antonov-2. Z-Max GPS receivers for reference point measurements were used. Geopositioning has been achieved by the inertial navigation system Trimble 750 GPS - Applanix POS/AV IMU. The spatial coordinates of reflected laser scans were determined. The ALTM 3100 operates in the infrared spectrum range, because low signals are reflected from the water surface. 
Other flight data: speed: 205 km/h, distance between strips axes – 300 m; side overlap – 30%; laser point density: 3-4 points/m²; average distance between points: 0.5 m. The accuracy requirement for scanner spatial positioning: standard deviations of less than 5 cm. Required accuracy for LIDAR measurements: for height points 15 cm, horizontal 30 cm.
Laser scanning data have been filtered, edited and Digital Surface Models were created. According to the morphological features the DSM was classified into the categories buildings, vegetation, bridges.

Digital aerial images. The images have been taken separately from the LIDAR flights using digital aerial camera UltraCamD (Vexcel Imaging, Austria), with a focal length of c₀ = 101,4 mm, frame size of 7500 x 11500 pixels. The flying height was 600 m. The created digital orthophotos have a scale of 1:2000. Spatial city models have been created by fusing LIDAR and orthogonal image data.

3. The accuracy of LIDAR images
The laser scanning accuracy depends on the scanner characteristics, the flight height, the scan angle, the laser beam frequency and distribution, positioning of the GPS-IMU system, the reflecting surface properties and some other factors. The LIDAR laser beam measures ranges to the solid surface with an
A significant systemic error was found.
LIDAR pulse point positioning has been investigated in the 24 reference (test) areas with asphalt covers. In the selected test areas there have been about 1000 control points identified and measured. Some LIDAR data accuracy analysis results are presented in Table 2.

Table 1: Results of LIDAR point heights accuracy investigation compared with geodetic control measurement

<table>
<thead>
<tr>
<th>Reflected surface</th>
<th>Number of control points</th>
<th>Accuracy assessments [m]</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean deviations</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test area – Kaunas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asphalt</td>
<td>74</td>
<td>-0.05</td>
<td>0.14</td>
<td>0.04</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Field</td>
<td>113</td>
<td>-0.08</td>
<td>0.17</td>
<td>0.10</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Field with brushes</td>
<td>119</td>
<td>-0.11</td>
<td>0.30</td>
<td>0.06</td>
<td>0.09</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Some results of laser pulse point position accuracy

<table>
<thead>
<tr>
<th>Test area/number of reference areas</th>
<th>Accuracy assessments according to the reference areas [m]</th>
<th>Height accuracy</th>
<th>Horizontal accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interval of deviations</td>
<td>RMS</td>
<td>Interval of deviations</td>
</tr>
<tr>
<td>Kaunas/ 3</td>
<td>-0.07 - (+0.06)</td>
<td>0.04; 0.04; 0.03</td>
<td>0.10 - 0.25</td>
</tr>
<tr>
<td>Vilnius/ 5</td>
<td>-0.10 - (+0.09)</td>
<td>0.09; 0.07; 0.08; 0.08; 0.05</td>
<td>0.10 - 0.22</td>
</tr>
</tbody>
</table>

4. Conclusions

Laser scanning from the aircraft combined with orthophotogrammetric data is useful for accurate land surface mapping and fulfils the requirements for the creation of spatial city terrain models.

The LIDAR pulse points positioning accuracy shows that the average standard deviation for height points is 0.05 - 0.12 m. The horizontal accuracy is 0.25 m when the flying height is about 1000 m and 1.26 m when the flying height is about 2000 m. The systematic errors can be reduced by calibration of the GPS, IMU and the scanner. The water surface absorbs electromagnetic energy significantly, especially when the carrier wavelength is about 1.5 µm.

It can be stated that, under the current accuracy the laser scanning data can be integrated with the orthophotographic base and is suitable for the creation of spatial 3D models for the urban surface, relief, buildings and other ground-based objects under large-scale topography and GIS needs.