Virtual Prototype for Robotics Applications: Laser Scanner Simulation with Adaptable Pattern

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Abstract — Today, Digital Prototyping and simulation technologies are used in the development of new technical systems and widely applied in research and industry. They allow cost- and time-efficient tests in all stages of development and support decision making. The sensor simulation component represents an important aspect in many simulation scenarios, especially in robotics applications. This paper focuses on the modelling and simulation of a laser scanner with adaptable pattern and is motivated by the development of a space qualified 3d laser scanner system for autonomous orbital rendezvous and docking. It continues work on a single ray based 2d laser scanner simulation for localization and mapping of mobile robots on planetary surfaces.

Keywords - laser scanner simulation, adaptable patterns, sensor simulation

I. INTRODUCTION

Developing new complex technical systems is a cost-intensive and time-critical process, especially for space applications. In the development process of new components, testing and verification are important tasks. With Digital Prototyping (DP), development time can be shortened, while the quality of products can be improved, as newly developed tools and algorithms are tested simultaneously. This paper focuses on a laser scanner simulation with adaptable pattern integrated into sophisticated Virtual Testbeds (VTs).

Providing simulated sensor data close to the physical prototype, the laser scanner simulation supports decision making already in the early design and development phase. Furthermore, development and testing of algorithms based thereon can be carried out in an early stage.

During the docking maneuver the sensor must function correctly for both large and even very small distances and provide additional information for example on reflection values.

The starting point of this implementation is described in [1]. In a previous project (SELOK), a single ray based 2d laser scanner simulation for localization and mapping of mobile robots on planetary surfaces was introduced. This simulation component was designed to meet the behavior of the physical component in use. Fig. 2 shows the results of this laser scanner simulation integrated into a Virtual Testbed for mobile robots on planetary surfaces.

As the requirements of the physical sensor component in the orbital RVD scenario are more complex, the corresponding simulation component needs to be revised and generalized. A challenging aspect in this context is that the
design of the physical component is not yet finalized. Consequently, the simulation component must be kept as flexible and modular as possible to be easily adopted to changes in design or behavior of the physical component. In addition, the newly developed laser scanner simulation component should be capable to simulate future laser scanner sensors without high development effort.

In the following section, a short overview in laser scanner simulation is presented. The concept and system architecture of the newly developed laser scanner simulation will be introduced in Section III. Section IV shows first results of the simulation component in the RVD scenario, as well as first evaluations. Finally, Section V concludes this contribution and suggests future developments.

II. RELATED WORK

Simulation of laser scanners has been studied in different domains since their physical counterparts are available. Examples for laser scanner simulations are airborne laser scanning [2], space exploration [3] or LiDAR simulations for forest measurements [4]. Furthermore, laser scanners have come to be extensively used in mobile robot applications. [5] describes a laser scanner simulation for a probabilistic object tracking application. [6] introduces a laser scanner simulation in the context of a general robot simulator which is for example simulating mobile robots playing soccer. In this example, the mobile robot requires sensor data to identify objects in the surrounding environment like other players, to localize on the playing field or to plan a way to score. [7] describes the use of simulated sensors like laser scanners in the domain of autonomous car testing. Other well-known examples for (mobile) robot simulators are USARSim [8] and Player/Stage/Gazebo [9] featuring sensor simulation components including LiDAR.

Simulation and modelling of 3d laser scanners is described in [10] and [11], but the implementations are focused on dedicated hardware and do not allow flexible pattern generation. To achieve realistic and close-to-reality sensor data, a laser scanner simulation requires error modeling, filter algorithms and specific modules to adapt characteristics of selected systems. [12] introduces methods to simulate laser scanners on graphics hardware resulting in accelerated processing speed and more realistic effects for example using depth rendering instead of ray tracing and, in addition, bump mapping techniques. Examples of this kind of optical sensor simulation are exemplarily shown in Fig. 3.

III. CONCEPT OF NEW LASER SCANNER SIMULATION

Starting point of the newly developed laser scanner simulation with adaptable pattern is a single ray based simulation of a 2d laser scanner integrated in our simulation system as described in [1].

It provides methods for the modeling, simulation and visualization of a wide range of sensors. It also offers a consistent data interchange within the simulation environment while the introduction of various error models enable the detailed analysis of sensor data processing algorithms under different boundary conditions. The underlying principles, especially of the optical sensor simulation, have been introduced in [14] and [15].

Figure 3. Left to right: Visualization of a laser scanner simulation using available rendering data and rendering techniques in simulation system VEROSIMTM as introduced in [13]. Each length of the reflection vectors illustrates how much light of the laser ray is diverted by the surface.

The existing single ray based simulation of a 2d laser scanner imitates the behavior of a physical 2d laser scanner which uses a fix rotation frequency and a given resolution. Therefore, it uses a high-resolution scheduler, calculates the line-of-sight of the sensor and determines the sensor data (for example depth) calling the underlying render based algorithms in time steps that can be achieved by real systems. This allows for an estimation of influences based on the motion. Thus, distortions and shifts can be explained in the scan data and algorithms can be implemented to attenuate the impact of these effects. To customize the behavior of this simulated sensor regarding a full circle scan, only two parameters had to be modified: the resolution and the scan frequency.

Regarding the new 3d laser scanner simulation, a different behavior was intended. Among other new improvements, it should feature a flexible generation of scan patterns and modelling of line-of-sight errors. Therefore, the existing sensor simulation had to be extended by a new scan mode. Instead using a monolithic approach in the implementation, the new simulation mode is implemented by modular building blocks. If necessary, it can easily be extended, for example when a new scan pattern is required that is not yet supported by the sensor framework.

As the underlying render based algorithms are implemented independent from the sensor simulation component and provide functionality through interfaces, no adjustment has to take place here. Hence, the effort to add the 3d laser scanner simulation to the existing sensor...
framework is very low, as already existing parts have to be reorganized in new flexible and parameterized modules.

Fig. 4 illustrates the aforementioned system architecture. The module “Sensors” contains the abstract base implementation for all sensors as well as abstract implementations for different classes of sensors, for example laser scanners, cameras, IMUs. The implementation of the simulated laser scanner with adjustable pattern is derived from this base class:

(“SimulatedLaserScannerWithAdjustablePattern” in module “SimulatedLaserScanner”) using additional abstract classes to differentiate between different types with specific characteristics. The abstract class:

“SimulatedLaserScannerWithAdjustablePattern” within the “Sensors”-module adds the important feature to use patterns.

The advantage of this system design is, that even at simulation runtime a new pattern can be selected and used. Furthermore, new patterns can easily be defined and implemented by overwriting the function defining the pattern behavior. The pattern itself uses a reference to define an optional line of sight error for more realistic behavior.

In each simulation step, the pattern generator receives a time stamp generated by the core laser scanner module. Based on defined parameters like azimuth and elevation scan frequency and azimuth and elevation scan interval, the line of sight is determined taking into account the optional modelled line-of-sight error. In a post-processing step, further error models and filters can be applied.

![Implemented patterns as proof-of-concept. Clockwise: Lissajous pattern, Rosette pattern, Spiral pattern and Rosette pattern again with different parameter set.](image)

**IV. APPLICATIONS AND RESULTS**

Starting point of the newly developed laser scanner simulation with adaptable pattern is a single ray based simulation of a 2d laser scanner. It is part of a sensor framework, integrated into our simulation system called VEROSIM™. In order to use the new laser scanner simulation in a Virtual Testbed, appropriate patterns had to be implemented. Based on [16], three typical scan patterns for space qualified laser scanners are recommended. Lissajous pattern, Rosette pattern and Spiral pattern. Each pattern has its advantages for a specific application.

The Lissajous pattern has a high point density in the corners. This might be an advantage when monitoring transitions at the edges. The pattern with the highest point density in the center area is the Rosette pattern while having the lowest point density at the periphery. Therefore, it is ideal to track objects if it is confirmed that these are in the center area. The Spiral pattern can be used as general purpose pattern as the scan is performed uniformly over the scan area. The aforementioned patterns are shown in Fig. 5.

The Lissajous pattern (1), the Rosette pattern (2) and Spiral pattern (3) can be described by the following formulas

![Diagram illustrating the system architecture with abstract and base classes.](image)
where $\phi$ and $\theta$ define the azimuth and elevation value for a given timestamp $t$.

$$\begin{pmatrix} \phi \\ \theta \end{pmatrix} = \begin{pmatrix} \sin(2\pi f_a \cdot t) \\ \sin(2\pi f_e \cdot t) \end{pmatrix}$$  \hspace{1cm} (1)

In (1) $f_a$ and $f_e$ define the azimuth and elevation scan frequency.

$$\begin{pmatrix} \phi \\ \theta \end{pmatrix} = \begin{pmatrix} \sin(2\pi f_a \cdot t) \\ \cos(2\pi f_e \cdot t) \end{pmatrix}$$  \hspace{1cm} (2)

In (2) $f_r$ and $f_a$ define the radial and rotational frequency.

$$\begin{pmatrix} \phi \\ \theta \end{pmatrix} = \alpha \cdot f_r \cdot t + \begin{pmatrix} \sin(2\pi f_a \cdot t) \\ \cos(2\pi f_e \cdot t) \end{pmatrix}$$  \hspace{1cm} (3)

In (3) $\alpha$ is used to parametrize the density of the spiral.

Furthermore, a parameterized line-of-sight error generator has been implemented (see Fig. 6). It uses a Gaussian distributed error model to generate falsified encoder values for azimuth and elevation, which are returned to the core simulation component to reorientate the scanner.

![Figure 6. Lissajous pattern with line-of-sight error in a simple test scene.](image)

In addition, and as a proof-of-concept, error models for systematic depth error, as well as a depth dependent error model have been implemented as shown in Fig. 7.

![Figure 7. Laser scanner simulation with additional depth dependent error. Red lines indicate the laser beam. Black dots are falsified hit points. In an ideal simulation run, all hit points are exactly on the gray board.](image)

![Figure 8. ATV approaching the ISS in VT while scanning. Red lines indicate the sensor data of the last performed simulation steps. Color coded dots represent hit points on the target (ISS).](image)

![Figure 9. Newly developed laser scanner simulation integrated into another Virtual Testbed for rendezvous and docking missions of two satellites.](image)
In a next step, the laser scanner simulation with adaptable patterns, as well as implemented error models, filters and visualization components have been integrated in Virtual Testbeds to verify the operational capability. As mentioned in the introduction, this specific sensor simulation is intended to support the development process of a space qualified 3d laser scanner system in rendezvous and docking missions. Therefore, it has been integrated in models of the Virtual Space Robotics Testbed (as shown in Fig. 8 and Fig. 9).

The performance of the simulation component depends on the complexity of the simulation model in use. The underlying render module to support the sensor simulation can be run in real-time. Tests in different Virtual Testbeds emphasize this capability. As an example, this was tested in a Virtual Testbed with 3 million vertices. The simulated laser sensor was parametrized to perform 1440 render calls per second for sensor simulation in single thread mode without rendering the scene for graphical output. The test was carried out on a desktop PC with an Intel Core i7-3770 which was supported by a NVIDIA GeForce GTX 680.

Additional to the depth value corresponding to an azimuth and elevation the underlying render module provides data for example for reflection. A filter has been implemented as proof-of-concept to count hits on specified materials.

In order to allow an external evaluation of the data as well as comparison of different simulation runs, an exporter to the point cloud library format (PCL) has been realized in addition to a simulation system immanent component to perform parametric sweeps [17].

In rendezvous and docking scenarios, for example retro-reflectors are in use to support data processing algorithms like position control. Using different parameter sets, it is possible to determine optimal parameters for azimuth and elevation scan frequency of a given pattern to maximize the number of hit points in a given scenario. Fig. 10 shows the results of two parameter sweeps in a static scene while altering the azimuth scan frequency for a Rosette pattern and a Lissajous pattern.

V. CONCLUSION AND FUTURE WORK

In this paper we introduced a sophisticated laser scanner simulation with adaptable pattern. It is based on a single ray approach. The newly developed sensor simulation extends an existing sensor framework integrated in a simulation system for mobile, industrial and space applications.

On the basis of this new approach, robot applications using a laser scanner with varying azimuth or elevation speed can be developed, analyzed and optimized. Especially dynamic effects, which result from the motion of the carrier
system or other dynamic elements in the simulated scene, can now be considered in detail.

The single ray based laser scanner simulation is capable of running in real time on current PC systems and benefits from modern graphics hardware. The underlying module provides information additional to the determined depth values and allows new applications. By introducing adaptable patterns, the newly developed laser scanner simulation is capable to be adopted to a variety of new domains and systems. Fig. 11, 12 and 13 illustrate examples in a disaster scenario, in an industry and an outdoor application.

Primary intention was the development of a 3D laser scanner simulation. By parameterizing, 1D and 2D laser scanner sensors can be simulated as well. Implemented patterns allow to cover a variety of laser scanner sensors.

In addition, it is easily possible to integrate more patterns without changes in the implementation of the core simulation component. Together with the underlying overall simulation system, the sensor simulation provides a holistic but comprehensive software tool for research and development and supports users in decision making regarding sensor components and the parametrization.

In the future, the newly implemented approach has to be validated for the sensor in development. At the moment, this task cannot be carried out as the physical laser scanner is not available yet. As soon as the prototype is available, an existing pattern will be parametrized to meet the requirements or a new one will be added.

For now, real data of the predecessor model is used. Here, well documented reference experiments have been carried out, for example with a perforated plate as shown in Fig. 14. The physical test has been repeated in the corresponding virtual testbed.

Currently, the simulated laser scanner data differs 0.0007m on average from the real sensor data (respectively 0.04%). Fig. 15 visualizes sensor data of the physical sensor on the left and simulated data on the right to illustrate first results.

Furthermore, reference experiments have already been carried out with an industrial laser scanner and have been compared to simulated data. Results of this process have been documented in [1].

For the final validation process, it is planned to carry out a test series with defined reference experiments which can be reproduced in sufficient Virtual Testbeds. We plan to do this at the German Research Center for Artificial Intelligence (DFKI). Therefore, detailed 3D laser scans of the test environment have already been performed. In the following, this data will be used to model appropriate virtual testbeds. During this measurement campaign, sensor data shall be recorded on static as well as dynamic targets.
Figure 15: Color coded visualization of depth values of the physical laser scanner (left) and the simulated one (right) in comparison.

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