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Indoor Localization System based on Galvanometer-Laser-Scanning for numerous Mobile Tags (GaLocate)

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Abstract—**Precise indoor localization of robots in intralogistic areas is of significant value in modern production. For this scenario we developed a pure optical localization system, consisting of a laser scanner and numerous mobile tags mountable on robots. The scanner searches and follows the mobile tags in the production hall continually. The tags receive the laser beam and determine their position with respect to the scanner. By the solid angel of laser beam deflection (angle of arrival) and separate infrared communication the position is generated. The system is full multi-target capable at low price for each tag. Furthermore, the data are directly available on the mobile tag. In this paper we describe the key components and algorithms of our localization system. We measured the scanning performance and maximum range of the optic components to optimize the first prototype.**

Keywords—**Laser localization system, multi-target, laser-scanning, burst mode receiver**

I. INTRODUCTION

The way of producing goods has changed in recent decades. Concepts of large warehouses and central production control are superseded by just in time production and kanban. These save costs and warehouse space and permit more flexible customer requests [1]. Just in time production asks for monitoring and localization of even small amounts of goods during the whole production run. Another aspect of modern production is the steady flow of goods supported by autonomous transport vehicles (ATVs). This leads to a main objective: Precise localization of robots and intelligent containers in automated production areas.

Systems based on RF (radio frequency) and ultrasonic suffer from low accuracy and multipath propagation [2] [3] which is due to reflections on walls and objects which can lead to false distance measurements. Production halls often harbor large machines, generating electromagnetic distortions. Optical laser systems have an inherent line of sight condition which can interrupt the measurement. In industrial environment absent measurements are to be preferred to false measurements. Consequently the research on precise industrial indoor navigation systems is focused to approaches based on laser [4].

In this paper we present a novel, pure optical localization system based on galvanometer-laser-scanning called GaLocate. The main purpose of GaLocate is to optically provide two-dimensional localization data, so that it is robust against electromagnetic field interference. The set-up efforts should be low to install the system rapidly and with only minor modifications of the robots. Finally, the localization costs for each mobile object should be low to be applied to numerous objects.

After discussing related work in the following section, our solution is presented together with the used algorithms and theoretical performance. The hardware consisting of scanner and mobile tags is described in detail in Section IV and V. In Section VI, the key components of GaLocate are characterized. Finally, Section VII concludes the paper and gives a short outlook on future research.

II. RELATED WORK

Traditionally, ATVs localize themselves in warehouses using inductive wires in the floor, but this solution is very inflexible. If the inductive wiring has to be changed, high costs arise due to a long production stops. In newer concepts optical localization methods are used like in the cellular transport systems from Fraunhofer IML [5] and the KARIS system [6]. There, the robots are equipped with laser line scanners which determine the distance from the robot to every circumjacent object in one horizontal plane. Simultaneous Localization and Mapping algorithms (SLAM) [7] try to assign this distance profile to a certain location on a map without the need of infrastructure. This approach may fail in production areas, which are dynamic compared to warehouses. People enter the robot area and objects like pallets lie about which can lead to inconsistencies in the internal map of the algorithm. Another difficulty occurs in very regular environments where no characteristics can be descried. Finally, self-localization with laser-optics and complex algorithms always implies high costs for each robot.

In [8] we presented a prototype localization system called MTOPS (Multi Target Optical Positioning System). This systems consists of a Laser Base Station (LBS) and several Active Position Receivers (APR) as shown in Fig. 1. The LBS

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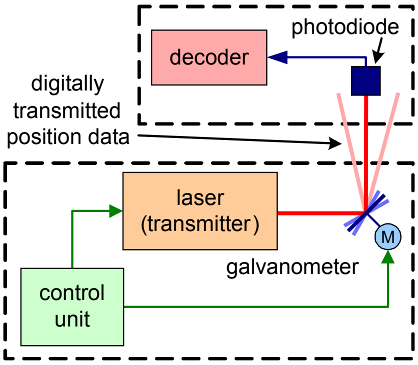

Figure 1: Schematic working principle of MTOPS with a Laser Base Station (LBS) and one Active Position Receiver (APR). The system uses a laser beam for localization as well as for optical communication [8].

performs a line-by-line scan in the measurement range and digitally transmits the current solid angle of the radiated laser beam, using the beam itself. The APRs receive the solid angle data by a photodiode. Generally, this setup is a reverse Angle of Arrival (AoA) measurement setup, known from RF localization systems [9]. It is notable that the localization data is directly available at the APR and that high resolutions are possible due to precise galvanometer beam deflection. In terms of camera-based systems the resolution equals 4 GigaPixel. Drawbacks of MTOPS are the low scanning performance and range. The low performance is related to the homogeneous scanning of the whole area, which is necessary because the scanner receives no feedback of the tag position. The range is limited by the free air burst mode communication.

Another laser-based concept is the iGPS from Nikon (former Metris) [10]. The iGPS is a 3D, modular, facility-wide scaled volume tracking system designed for industrial applications. The operation of iGPS is comparable to a GPS where satellites are replaced by infrared iGPS laser transmitters (Fig. 2) activating a measurement field as large as the entire facility. Tools, parts and probes can be equipped with iGPS receivers which perform a self-localization. As such, positions and orientations can be measured or dynamically tracked during the production run. Measurement repeatability and uncertainty are in the sub-millimeter range. The costs compared to other solutions are very high (minimum cost of deployment is around $180.000).

Camera-based concepts like Motion Capture have a slightly lower resolution. The objects are featured with retroreflective balls which are illuminated by a strong infrared source. Several cameras oriented in different angles record the balls. The position is calculated with pattern detection and 3D algorithms. The main disadvantage in a multi-target scenario is that it is a pure external localization system. It is not possible to assign the gathered information to a particular object.

III. SOLUTION OVERVIEW

The localization system presented in this work is based on the already mentioned Multi Target Optical Positioning System (MTOPS) which was also intended to be suitable for the production hall requirements. Similar to MTOPS the ATVs are equipped with mobile tags which are scanned by a laser scanner mounted on the ceiling of the production hall as shown in Fig. 3. Some hardware components like the galvanometer scanners are reused but a new operating principle was implemented.

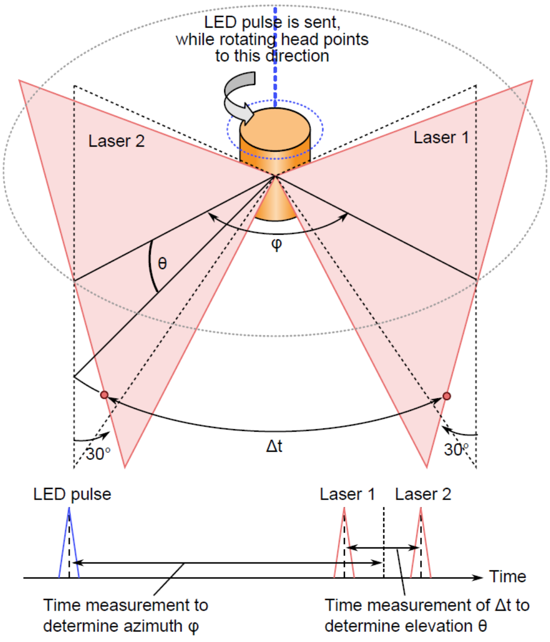

Figure 2: The transmitter consists of two line lasers, which are tilted by 30° against the vertical axis. The elevation θ is determined by measuring the time between the detection of laser 1 and laser 2. The period between the detection of the LED pulse and the mean in time of laser 1 and laser 2 is used to determine the azimuth φ. [10]

The main challenge is to increase the scanning performance. To strike the small photodiode in a distance of several meters, a very fine scanning is required. This is very slow if it is applied to the whole measurement area. Hence the mobile tags are equipped with retroreflectors which are more likely to be crossed by the laser. The scanner detects the reflection and thus gets a feedback of the tag position to confine the scanning.

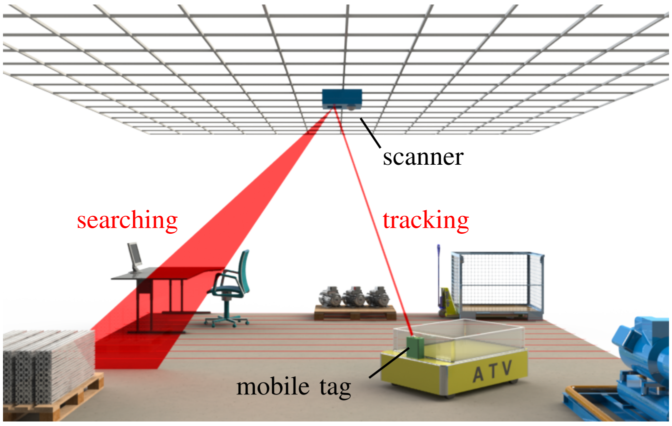

Figure 3: Illustration of a scenario with GaLocate in a production hall. A laser scanner is mounted under the ceiling, searching and tracking the mobile tags which are mounted on the transport vehicles.

The second challenge of this work is to get rid of the delicate burst mode free air communication which limits the MTOPS prototype to a range of 0.225 m. In GaLocate the angles of the laser beam deflection are transmitted via high-speed infrared communication to all mobile tags. In the center of the reflector a small photodiode is placed which is read-out by a high-speed burst mode amplifier. During the scanning process this photodiode determines the exact point in time of laser beam crossing and hence links the infrared position data to the tag. As a result the data transmission is simplified to a laser beam detection.

Similar to MTOPS the localization data is directly available at the mobile tag. Beyond this, it is possible to avoid collisions, because the positions of all tags are receivable to every tag on every robot due to the omnidirectional infrared communication.

A. Scanning algorithm

At the beginning of each scanning cycle, the laser beam is moved in a meander search pattern through the hall as depicted in Fig. 4. This pattern is very rough compared to the size of the reflectors (pattern to reflector ratio $r_{\text{pattern}} = 8$). To achieve a sufficient scan coverage anyhow, the scanning is repeated with a cycling offset. Once the scanner receives a reflection from a tag, the angles of current laser beam deflection are stored in a list. After completing the search scan, all positions in the list are scanned again with high resolution. This is done separately for x and y to provide the position data for the mobile tag in both dimensions.

The reflections of the fine scan are evaluated with a circle fit algorithm [11] to determine the center of the reflector. The corresponding list entry is updated with this new position. As a result the objects are tracked via repetitive fine scanning. If an object is no longer detectable, it is removed from the list. The full algorithm of scanning is shown in Fig. 5.

B. Scanning performance

In the following we estimate some operating figures of the system using the approximation $\tan\varphi = \varphi$. The galvanometer scanners have a rated angular excursion of $\varphi_{\text{full}} = \pm 28^\circ$ (approx. 1 rad) which is divided into 2^{16} steps leading to a theoretical step size φ_{step} of 15 µrad [12]. We assume for all following calculations the difference in height h from mobile tag to scanner on the ceiling of the production hall to be 4 m. The resolution a_{min} at level of the mobile tags is then

$$a_{\text{min}} = \varphi_{\text{step}} \cdot h = 60\,\mu\text{m}. \tag{1}$$

Object sizes w can be expressed as a multiple of a_{min} in the unit of steps. The circular reflector on the tag has a diameter of $a_{\text{tag}} = 40\,\text{mm}$ which is scanned during tracking mode in an enclosed square of 60 mm × 60 mm, related to a scanning width of $w_{\text{track}} = 1000\,\text{steps}$. The distance between two scanning lines determines the resolution as well as the scan repetition rate f_{system} of the system. We evaluated to take $n_{\text{track}} = 125$ lines in tracking mode resulting in a resolution of 480 µm which is about half of the photodiode chip diameter of $a_{\text{diode}} = 1\,\text{mm}$. In searching mode $n_{\text{search}} = 16$ lines turned out to be convenient.

The maximum scanning speed v given in steps/s depends on the scanning width w as shown in Section VI. For this estimation we consider $v_{\text{search}} \approx 50 \times 10^6\,\text{steps/s}$, which is the speed in full range searching mode ($w = 65\,536\,\text{steps}$) and the speed in fine scanning mode $v_{\text{track}} \approx 12 \times 10^6\,\text{steps/s}$ ($w = 1000\,\text{steps}$). The scan repetition rate of the system to track $m = 3$ mobile tags can be calculated to

$$f_{\text{system}} = \left(\frac{2^{16} \cdot n_{\text{search}}}{v_{\text{search}}} + m \cdot \frac{2 \cdot w_{\text{track}} \cdot n_{\text{track}}}{v_{\text{track}}} \right)^{-1} = 12\,\text{Hz}. \tag{2}$$

In comparison the MTOPS prototype yields a performance of 1.1 Hz, but with a scanning line width at the floor of 15.4 mm, which is an insufficient scan coverage. From the system performance f_{system} of GaLocate, the maximum velocity v_{max} of a moving robot and the unique searching time t_{search} for a former unknown robot can be derived.

$$v_{\text{max}} = \frac{w_{\text{track}} \cdot a_{\text{min}}}{2} \cdot f_{\text{system}} = 0.36\,\text{m}\,\text{s}^{-1} \tag{3}$$

$$t_{\text{search}} = \frac{r_{\text{pattern}}}{f_{\text{system}}} = 0.67\,\text{s} \tag{4}$$

With our concept the burst mode communication is replaced with laser burst detection. Nevertheless, the time of laser beam crossing on the photodiode t_{diode} is very short and can be calculated from the scanning rate v_{track}, resolution a_{min} and diameter of the photodiode a_{diode} by

$$t_{\text{diode}} = \frac{a_{\text{diode}}}{a_{\text{min}} \cdot v_{\text{track}}} = 0.34\,\mu\text{s}. \tag{5}$$

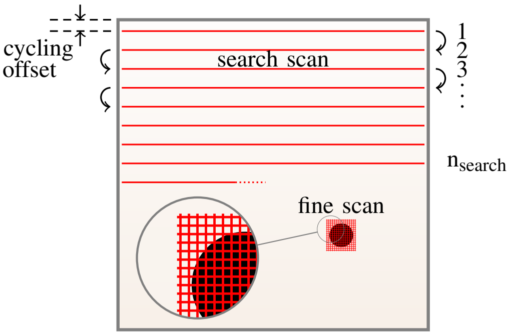

Figure 4: The scan pattern is performed in a meander shape for both the searching and fine scanning. The fine scan is done for x and y separately.

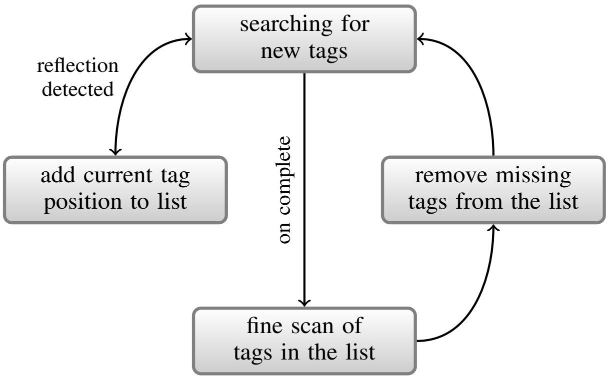

Figure 5: Flowchart of the scanning algorithm with alternating searching and fine scan mode. Detected mobile tags are managed in a list.

The laser beam is pulsed with a certain frequency f_{laser} to get a high signal to noise ratio. The receiver on the tag is very sensitive to that frequency. According to Nyquist's sampling theorem, the laser frequency must be at least double of $1/t_{\text{diode}}$. We choose

$$f_{\text{laser}} = 4/t_{\text{diode}} = 12\,\text{MHz}. \tag{6}$$

As shown in Section V, it is possible to detect frequencies in this range even with a relatively compact circuit.

IV. GALOCATE - SCANNER

A. Optics

The optics is designed to move the laser beam through the production hall and detect reflections from the tags. To perform the scanning, the laser beam is deflected by two mirrors which are pivoted by a moving-magnet galvanometer-based optical scanner from Cambridge Technology (Model 6215H). Each galvanometer is driven by its own driver board to reduce electrical crossover effects. The driver boards are enhanced with lowest ESR capacitors to supply high peak currents at fast mirror turns.

The optical path with reflection detection is the following: The laser light is emitted by a 1 mW laser module, passes a beam splitter and is then deflected by the aforementioned galvanometer mirrors. If the beam hits a reflective tag, the reflected laser light passes the galvanometer mirrors again. The beam splitter deflects a certain portion of incoming light from the original light path. A convex lens with $f = 30\,\text{mm}$ concentrates the light to a spot on the receiver photodiode. To maximize the light intensity on the photodiode, we use a 50:50 beam splitter. All components are mounted on a solid aluminum plate, which is shown in Fig 6.

B. FPGA and PowerPC

The laser scanner control unit has to manage time-critical galvanometer movements and infrared communication while concurrently execute algorithms preferably formulated in high level language. Thus, a conjunction of FPGA (field programmable gate array) and microcomputer is a convenient solution. For our prototype, we use a AES-V5FXT-EVL30-G evaluation board including a Virtex-5 FPGA with a PowerPC core. Modules like the up and down counter for the galvanometers, laser modulation and infrared communication are described in VHDL. They are controllable via GPIOs connected to the processor local bus (PLB). The PowerPC is also connected to this bus as shown in Fig. 7.

The board features a high frequency capable expansion port. Signals in single-ended or in low voltage differential standard (LVDS) can be routed to this port to control the galvanometers and drive laser transmitting and receiving.

C. Laser transmitter and receiver

Laser transmitter and receiver are designed as two independent printed circuit boards (PCBs) also shown in Fig. 6. The laser module features one digital input pin (yellow) to switch the laser on and off. The transmitter circuit converts the LVDS signals from the FPGA to single-ended signal for this pin which is done by the high speed comparator TLV3501.

The laser receiver has to detect a sub-micronsecond burst of the modulated laser as shown in (5) and (6). Common fiber optic communication receivers are very fast but are designed for a continuous laser link. The usually included DC-cancellation in those receivers prevents burst mode receiving. Our receiver electronics consists of common electronic devices like a PIN-photodiode of type BPX65, an AD8015 integrated transimpedance amplifier and an LMH7220 high speed comparator with LVDS-output. These ICs are fully burst mode capable. A reflection signal is determined by a correlation of transmitted and received signal carried out in the FPGA.

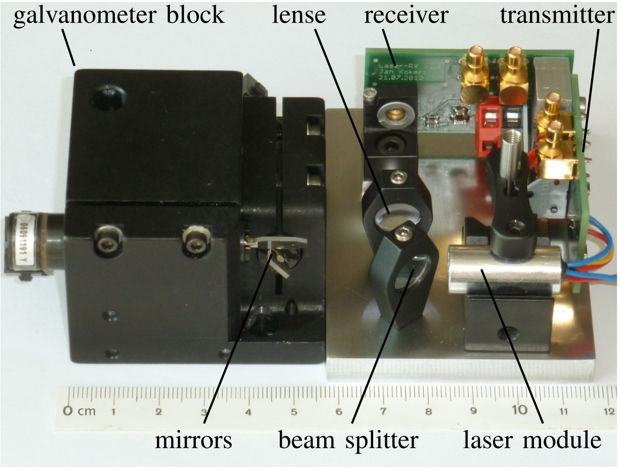

Figure 6: All optical components are mounted on a solid aluminum plate including the laser module, beam splitter and galvanometers.

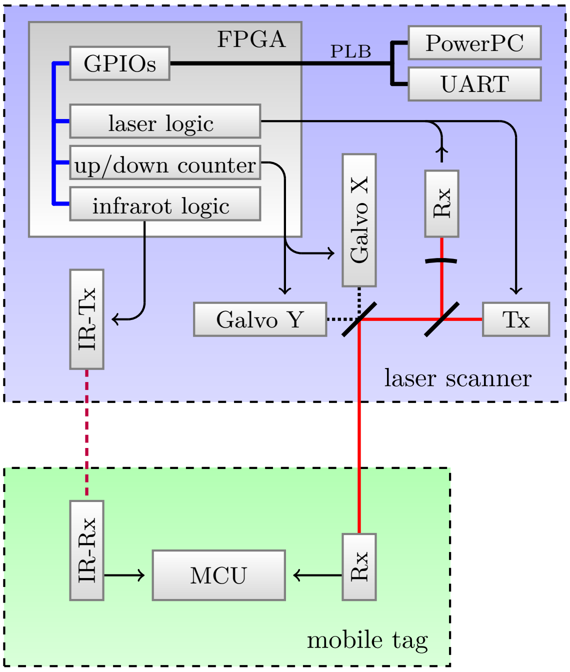

Figure 7: Schematic overview of all key components and their connections.

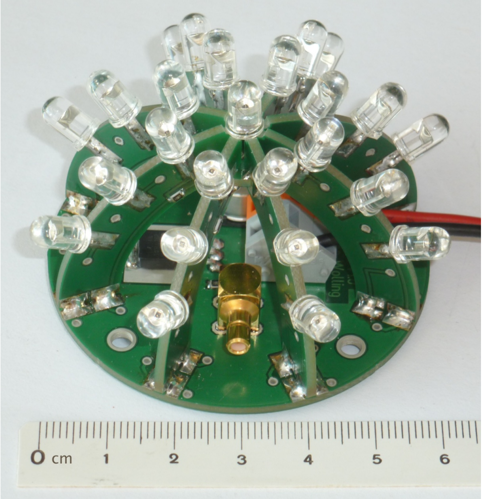

Figure 8: Several PCBs were plugged together to form a half sphere which is populated with 25 high power infrared LEDs.

D. Infrared communication

To transmit infrared data to all mobile tags a strong transmitter is needed. For this purpose a half sphere was built using several pluggable PCBs as shown in Fig. 8. The half sphere is populated with 25 infrared LEDs, all directed in different angles to ensure a uniform emission. Each LED has an optical output power of 50 mW resulting in 1.25 W total optical output power. The communication is based on bursts of different length at a carrier frequency of 455 kHz. The data transfer is organized in nibbles (4-bit) which requires 16 different burst lengths (25, 30, 35, ..., 100 cycles).

Before fine scanning of each mobile tag starts, data like tag ID and center position of the scheduled scan are transmitted to the tag. As the fine scanning starts, a short infrared trigger burst (10 cycles) is transmitted synchronously at each line in x and y direction. The mobile tags count the bursts while standing by for the detection of the assignment signal on the photodiode to eventually refine the originally transmitted position. At a carrier frequency of 455 kHz, the trigger signal is shorter than the time needed for one scanning line in fine scanning mode (about 22 µs vs. 83 µs) and therefore allow the described scanning and infrared transmitting synchronously. The mobile tags are equipped with a TSOP7000 integrated infrared receiver from Vishay. All components are mountable in one solid casing as shown in Fig. 9. The scanner has a dimension of approx. 180 mm × 160 mm × 100 mm at a total weight of less than 5 kg.

V. GALOCATE - MOBILE TAGS

As mentioned before, the mobile tags are mounted on the ATVs. They have to be compact and reasonable priced to enable scanning of numerous tags at low total costs. They must be detectable for the laser scanner by providing a retroreflector. Furthermore they shall detect laser beam crossing and synchronous infrared communication.

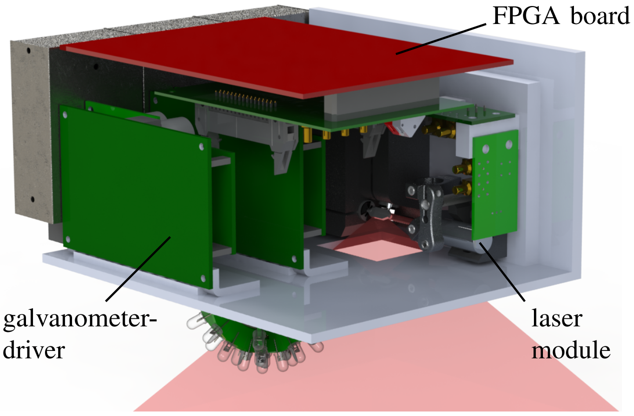

Figure 9: Rendering of the scanner casing with laser beam output (red). The infrared transmitter is placed at the bottom of the scanner casing.

A. Receiver circuit and frequency detection

The receiving circuit of the mobile tag is rather similar to the circuit used in the scanner. Differences are the photodiode (SFH 203 P) which has a wide half angle of ±75° and the implementation of the laser signal determination.

For the mobile tag a low cost alternative to an FPGA is needed, leading to an ATXmega32A4 from Atmel. This microcontroller features an event system which configures counters and comparators running parallel to the main program. Additionally, the Xmega offers a high clock rate of 32 MHz which can be further overclocked to 48 MHz. Instead of using the external comparator TLV3501, the internal one of the Xmega is used. On rising and falling edges events are generated which are routed to a timer configured to frequency capture mode. This timer counts the clock cycles during the edges which is proportional to the frequency and is therefore used for signal detection.

B. Mobile tag for demonstration

The mobile tag shown in Fig. 10 demonstrates how to receive localization data at low costs at the robot. The display at the

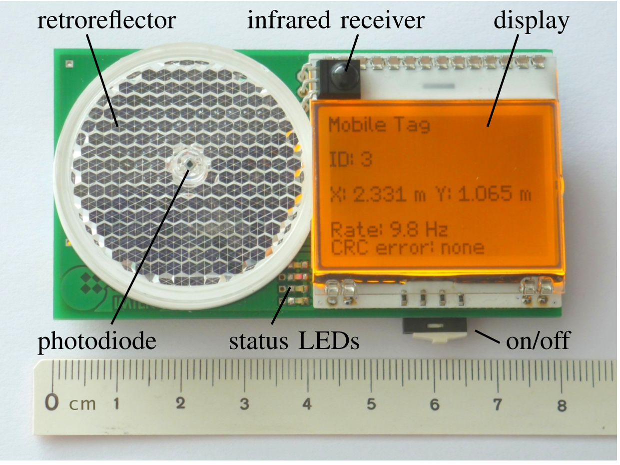

Figure 10: One of several mobile tags which is mountable on a robot. For demonstration purposes a display visualizing the localization data is added.

right shows all the information. A USB interface is included to transfer the data to the ATV control unit or to a PC for debugging purpose during development. The demonstrator is powered by a LiPo-battery which can be charged via USB.

VI. EXPERIMENTAL RESULTS

A. Galvanometer characterization

As mentioned in Section III, the maximum scanning speed is dependent on the scanning width. For performance calculation the determination of this dependency is necessary. The galvanometers are driven by a PID controller. Measurements at several scanning widths with increasing speed were carried out, until the scan control stops by emergency. Figure 11 shows the minimum stable step time t_{step} in dependence on the scanning width given in steps.

In a first approximation the scanning speed is limited by the acceleration of the galvanometer mirrors. Further limitations given by the PID controller are neglected. It is assumed that at the tipping points the galvanometer is driven with a constant and maximum acceleration A, given in steps per square second. For the high-value tipping point at time $t = 0$, the deflection angle φ is described by

$$\varphi = \begin{cases} v \cdot t & t < 0 \\ v \cdot t - \frac{1}{2} \cdot A \cdot t^2 & t \geq 0. \end{cases} \tag{7}$$

The maximum scanning speed v_{max} is reached if there is still a control deviation when the next tipping point is attained. From this condition, the relation

$$t_{\text{step}} = \frac{1}{v_{\text{max}}} = \sqrt{\frac{4}{A \cdot w}} \tag{8}$$

can be obtained. The deviation from the model at very small scanning widths is explainable by delays of the PID control.

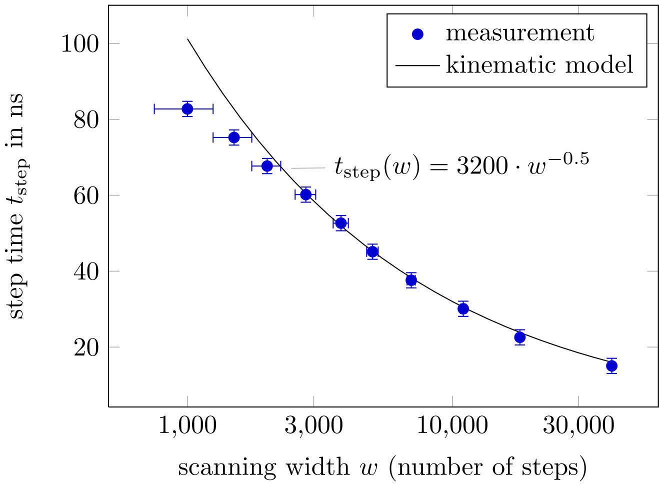

Figure 11: The measured galvanometer performance in comparison to a kinematic model assuming constant acceleration at the tipping points.

B. Retroreflector selection

Receiving a reflection of the mobile tag is the most critical part of the localization. The mirrors of the galvanometers are rather small (5 mm × 6 mm) so only a small amount of light can be focused on the receiving photodiode. In this experiment the maximum scanning distance using different retroreflectors was investigated as shown in Tab. I. The distance from the galvanometer mirrors to the reflector was increased continuously until the signal vanishes abruptly. This sharp transition is due to a fixed hysteresis of the comparator in the receiving electronic. The reflective foils show a stronger dispersion than hot-embossed triple reflectors and accordingly their retroreflective portion is lower. The size of the inverse pyramids (lattice size) of the hot-embossed reflectors determines the maximum beam displacement and therefore a finer one is preferable.

Table I. Different retroreflectors and their achieved range. The number in brackets is the grid size of the triple mirrors.

Retroreflector	Distance in meter
Oralite 5500 (foil)	0.80 ± 0.05
3M Scotchlite 8850 (foil)	1.9 ± 0.1
SICK REF-AC1000-56 (foil)	5.5 ± 0.1
Low cost bicycle reflector (2 mm)	6.5 ± 0.2
SICK No. 5313922 (4 mm)	9.0 ± 0.2
SICK No. 5313506 (2 mm)	10.0 ± 0.2
SICK No. 5308843 (1.3 mm)	13.0 ± 0.2

C. Infrared communication

The galvanometer scanners of GaLocate are the limiting component of the overall performance. The infrared communication should not slow down the scanning which is examined in the following. We measured the maximum range from infrared transmitter to the receiver on a mobile tag. Further the jitter was measured, which is important to distinguish between different burst lengths. Finally the worst case duration of data transmission and n_{track} triggers was determined. The comparison column shows the chosen design parameters and confirms that all infrared communication requirements are fulfilled.

Table II. Infrared communication measurements

Quantity	Result	Comparison
Range at direct line of sight	12.0 ± 0.5 m	≈10 m
Max. burst jitter at TSOP7000	±1 cycle	±2.5 cycles
Transmission time t_{data} (ID, X, Y)	4.4 ms	
Transmission time t_{triggers} (n_{track})	6.0 ms	
Repetition rate f_{ir} ($m = 3$ mobile tags)	32 Hz	12 Hz

Similar to (2) the infrared repetition rate of data and trigger transfer for m mobile tags is calculated by

$$f_{\text{ir}} = \frac{1}{m \cdot \left(t_{\text{data}} + t_{\text{triggers}}\right)}. \tag{9}$$

VII. CONCLUSION AND FURTHER RESEARCH

A new concept of indoor localization using galvanometer laser scanning was implemented. All key components of the system were tested successfully. The galvanometer speed is sufficient to search and follow several mobile tags with a sub-millimeter resolution. The scanning accuracy was approved to one step equaling 15.4 µrad. Retroreflectors are detectable by the optics to distances beyond 10 m to confine the scanning areas. The detection of sub-microsecond pulses of modulated laser light even with ordinary electronics was validated. Furthermore, the infrared communication meets all speed requirements and reaches a distance of about 10 meters.

Further research will be considered in the area of optimizing the prototype. The components of the scanner needs to be assembled into an industrial compliant casing. The scanning algorithm needs to be successfully completed and finally, the whole system has to be characterized to determine the resolution, the absolute position accuracy, and the repeat accuracy. The system can be up-graded to 3D if laser receiver and transmitter are equipped with a distance measurement unit based on time of flight. Equipping a production hall with several scanners is possible due to different laser modulation frequencies to increase the measurement area and mitigate the line of sight condition.

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