ISPRS Journal of Photogrammetry and Remote Sensing 99 (2015) 25–29

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Localization of mobile laser scanner using classical mechanics

Ville V. Lehtola [a,*], Juho-Pekka Virtanen [a], Antero Kukko [b], Harri Kaartinen [b], Hannu Hyyppä [a]

[a] Institute of Measuring and Modeling for Built Environment, Aalto University, P.O. Box 15800, 00076 Aalto, Finland
[b] Finnish Geodetic Institute, P.O. Box 15, 02431 Masala, Finland

ARTICLE INFO

Article history:
Received 30 May 2014
Received in revised form 29 October 2014
Accepted 29 October 2014
Available online 20 November 2014

Keywords:
Mobile
Scanner
Platforms
Design
LIDAR
IMU
Localization
Trajectory

ABSTRACT

We use a single 2D laser scanner to 3D scan indoor environments, without any inertial measurement units or reference coordinates. The localization is done directly from the point cloud in an *intrinsic* manner compared to other state-of-the-art mobile laser scanning methods where external inertial or odometry sensors are employed and synchronized with the laser scanner. Our approach is based on treating the scanner as a holonomic system. A novel type of scanner platform, called VILMA, is designed and built to demonstrate the functionality of the presented approach. Results from flat-floor and non-flat-floor environments are presented. They suggest that intrinsic localization may be generalized for broader use.

1. Introduction

Mobile laser scanning (MLS) answers to challenges where airborne laser scanners do not reach and terrestrial laser scanning (TLS) is too cumbersome. These challenges include indoor environments (Xiao and Furukawa, 2012; Liu et al., 2010; Holenstein et al., 2011; Thomson et al., 2013; Bosse et al., 2012), but also accurate measurement and modeling of some outdoor environments (Kukko et al., 2012; Bosse and Zlot, 2009; Barber et al., 2008; Kukko, 2013). The Achilles' heel of MLS is localization, or more specifically, the localization of data coming from a moving scanner with six degrees of freedom. An off-the-shelf answer is to deploy an inertial measurement unit (IMU) to track the movement of the MLS platform, i.e. to obtain its trajectory $j(t)$. This, however, leads into another problem, which is that finite inertial errors accumulate with time and without boundaries. To counter this, outdoor MLS can employ the global navigation satellite system (GNSS) for positioning to provide accurate reference points to the platform trajectory (Kukko et al., 2012). Indoors, however, the GNSS is not available.

In order to cope with the lack of inertial reference frame, such as the GNSS, indoor approaches then require prior knowledge to localize scan data. This prior knowledge typically includes assumptions about the environment that introduce side effects. The flat-floor assumption is commonly used, see e.g. Thomson et al. (2013), although it has problems with, for example, stairs. Xiao and Furukawa (2012) reconstructed museums with a trolley, assuming that all rooms are flat-floored and rectangular (even when they are not). Liu et al. (2010) modeled non-flat-floored indoor environments with a human-portable backpack, but the employed laser-image-fusion technique is yet limited to hallways only. Holenstein et al. (2011) reconstructed unstructured, large scale indoor environments (caves) with a 3D voxelized-volume-based approach that requires the model to be watertight and hence fails if an open sky or windows are present. Bosse et al. (2012) designed a spring-mounted 3-D range sensor that employs the laser data in a simultaneous localization and mapping (SLAM) scheme. The latter two approaches are intriguing, since they employ only one 2D laser scanner that is rotated in a way so that the whole 3D environment is captured, in contrast to the previous two approaches that both employ three 2D scanners. Practically, the simpler and cheaper a solution is, the better it is. As a continuum to scanner method design, Elseberg et al. (2013) and Bosse and Zlot (2013) present probabilistic SLAM methods that are among other means applicable for scanner trajectory post-optimization, thus effectively improving the quality and precision of the entire acquired point cloud.

In this paper, we propose an approach to localization through theoretical mechanics. In particular, an experimental device is constructed to verify if localization succeeds for a (holonomic)

* Corresponding author.

http://dx.doi.org/10.1016/j.isprsjprs.2014.10.008
0924-2716/

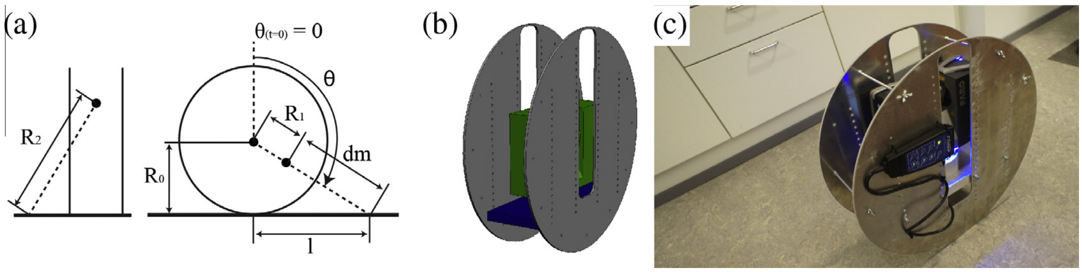

Fig. 1. (a) A schematic describing the path parameter $\theta(t)$ and constants R_0, R_1 and R_2. Measured distances are marked with d_m. (b) VILMA assembly schematics. (c) A 2D laser scanner, here Faro Focus 3D in helical mode, is attached in between two metallic discs so that it retains a wide viewing angle through the oval holes carved on the discs.

1D trajectory. Our device consists of a 2D laser scanner that is embedded between two round discs, effectively forming a rolling device. The scanner trajectory is reconstructed solely from the point cloud data. Two assumptions are required for this; that the device does not slip against the floor and that the floor is flat. No localization devices e.g. inertial or rotation measurement units are used. To our best knowledge, every approach so far has employed at least an IMU. The proposed approach paves the road for a MLS paradigm, where a sole 2D laser scanner is employed.

2. Proposed approach

The localization of the laser data requires a successful reconstruction of the sensor's path of movement. This path is formally known as a time-dependent trajectory $j(t)$ with six degrees of freedom, namely, three from location and three from orientation. We write out

$$j(t) = [\theta(t), \psi(t), \phi(t), x(t), y(t), z(t)]^T, \tag{1}$$

where θ is the pitch, ψ is the roll, and ϕ is the yaw angle. Time is denoted by t. Without any reference coordinate system, the successful reconstruction of the trajectory requires that these degrees of freedom are eliminated. If this is done so that the coordinates become subject to the constraint

$$f(\theta, \psi, \phi, x, y, z, t) = 0, \tag{2}$$

where f is a bijective function, then the system is *holonomic* (see e.g. Bloch, 2003). Otherwise, the system is *non-holonomic*. The difference between these is that in the first case, the localization can be done knowing only the initial and the current state of the system. In the latter case, the trajectory reconstruction by path integration requires accurate measuring of the position all along the path.

Consider MLS platforms in general. In order to capture a 3D environment with a 2D laser scanner, the scanner must be rotated about at least one axis.[1] If the 2D scanner is mechanically attached on a wheel, at a radius R, so that it can only rotate about one axis of rotation, rotational degrees of freedom are reduced by two, i.e. ϕ and ψ are constant. Furthermore, if this wheel is mechanically connected onto another wheel on which the mobile platform rolls, the sensor's movement follows a trajectory

$$j(t) = F(j_p(t)), \tag{3}$$

where $j_p(t)$ is the platform trajectory and F is a bijective function.

It is assumed that the platform trajectory j_p is continuous, and bounded to move on a 2D plane, i.e. on the floor. The platform trajectory is then a function of two time-dependent variables

$$j_p = j_p(r(t), \sigma(t)), \tag{4}$$

[1] For example, Faro Focus 3D scanner in 2D helical mode, which was used in our experiments has a field of view of 300°.

where $r(t)$ is the distance traveled and $\sigma(t)$ is the steering angle, i.e. the tangent of the trajectory at time t. Following the scope of this paper, it is assumed here that the platform moves dead straight, $\sigma(t) = const.$, $x = const.$, and that the sensor is mechanically attached to the rolling wheel, which does not slip against the floor. The solution for the sensor trajectory $j(t) = (x, y, z)(t)$ follows from the one for a contracted cycloid

$$\begin{cases} x = const. \\ y = R_0\theta + (R_0 - R_1)\sin\theta \\ z = R_0 + (R_0 - R_1)\cos\theta \\ \theta = \theta(t) \end{cases}, \tag{5}$$

where θ is the angle of scanner zenith in radians, R_0 is the radius of the cycloid, and R_1 is the scanner position on the radius, see Fig. 1(a). At the beginning, the zenith is pointing upwards, $\theta(t = 0) = 0$. Hence, $\theta(t)$ is the path parameter that describes the scanner trajectory, and obtaining it solves localization.

In order to obtain $\theta(t)$ from the data, a following concept is proposed. Each time the 2D scanner is perpendicular towards the floor (PTF), $\theta(t) = \pi + 2\pi n$, $n = 0, 1, 2, \ldots$, the scanning distance reduces to minimum R_1. We call this a PTF-observation, and keep track of these occurrences in the laser data series obtaining a time series $\{t_1, t_2, t_3, \ldots\}$. We will discuss in Section 4, how the PTF observation is used in determining the phase of the rolling sensor. Here, we note that the PTF observation is robust to error, since data points from a large field of view can be used to interpolate the floor point precisely below the sensor. Also, stochastic errors in PTF observations do not cumulate with time as long as the no-slip condition with the floor applies.

3. Concept realization

3.1. The build

The build of our experimental device, named VILMA, is depicted in Fig. 1. The radius of metal discs is $R_0 = 250$ mm. Faro Focus 3D laser scanner is mounted between the discs in helical 2D mode. 2D scans were conducted with 95 Hz frequency capturing 8534 points per a 300° field of view. A 1, 5 mm thick silicon ring padding was used to protect the scanner from tremor caused by dirt. With the padding, the distance covered with one rotation is 1572 mm. Based on this measure, the relative error in disc radius due padding elasticity is ±0.1%.

Experiments were conducted both in a controlled laboratory environment i.e. a hallway, see Fig. 3(a), and in a rough environment, in an underground car park, see Fig. 3(b). The floor of the car park was covered with small particles, sand and dirt, and was sloped to direct water to the drains, implying that VILMA's altitude and rolling velocity change somewhat arbitrarily. VILMA was set to roll by a gentle manual push. When it started to slow down, another push was given, taking care that the rolling direction