Terrain Traversability Analysis for off-road robots using Time-Of-Flight 3D Sensing

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1. INTRODUCTION

One of the key challenges for outdoor mobile robots is to navigate autonomously in an unstructured and dynamic environment. When autonomous robotic systems leave the protected lab environment and operate in unstructured outdoor environments, they need to estimate the traversability of the terrain in order to navigate safely.

Traversability estimation is a challenging problem, as in a non-structured environment one should consider both the terrain characteristics, such as slopes, vegetation, rocks, soils, etc. and the robot mobility characteristics, i.e. locomotion method, wheels, etc [9,10]. It is thus required to analyse, in real-time, the 3D characteristics of the terrain and pair this data to the robot capabilities.

Traditionally, stereo cameras or 3D laser range finders are used as input devices for traversability analysis. However, both sensing modalities have important disadvantages. Stereo requires processing-intensive feature-matching processes, which fail on unstructured terrain, whereas 3D laser range finders are very expensive and limit the movement speed of the robot. To avoid these problems, we present in this paper a methodology toward terrain traversability analysis methodology using as input a time-of-flight (TOF) camera.

The presented terrain traversability analysis methodology classifies all image pixels in the TOF image as traversable or not, by estimating for each pixel a traversability score which is based upon the analysis of the 3D (depth data) and 2D (IR data) content of the TOF camera data. This classification result is then used for the (semi) – autonomous navigation of two robotic systems, operating in extreme environments: a search and rescue robot and a humanitarian demining robot. Integrated in autonomous robot control architecture, terrain traversability classification increases the environmental situational awareness and enables a mobile robot to navigate (semi) – autonomously in an unstructured dynamical outdoor environment.

2. SYSTEM SETUP

2.1. Vehicle description

The platform used as a test bed for the terrain traversability analysis is shown in Figure 1. The base vehicle of this unmanned platform consists of an Explosive Ordnance Disposal (EOD) robot tEODor, a heavy outdoor robot. We chose to use a standard EOD robot platform for several reasons:

- As a platform, it has proven its usefulness in dealing with rough terrain with excellent manoeuvrability and good off-road performance.
- With a payload of around 350 kg, it makes it possible to carry multiple sensors and on-board processing equipment.
- The rugged design of the platform makes it capable of handling unfriendly environmental conditions.
- Recycling a standardized platform is a good means of saving costs and avoiding buying expensive dedicated platforms.

An important drawback of the standard tEODor platform is that it does not feature any autonomous capabilities. To overcome such a constrain and be able to execute (semi) - autonomous tasks the platform was upgraded with the necessary electronics, sensors, computing power, motor control units and power sources [1].

Figure 1: The system setup, consisting of the UGV tEODor base, UAV and an integrated active Time-Of-Flight Depth sensing system

In order to provide required data input to the terrain traversability analysis and path negotiation algorithm, an active depth sensing system was integrated on the platform. This 3D sensing system consists of a PMD CamCube 3.0 time-of-flight sensor mounted on a pan-tilt unit. The time-of-flight camera is in a tilted angle to avoid typical signal modulation problems. Additionally, we have considered using a small quad-rotor based unmanned aerial vehicle (UAV) for assistive collaborative mapping. The idea of using this UAV is to pair the advantage of a UAV (possibility to obtain a good overview of the environment from above) with the advantages of a UGV (possibility of interacting on the terrain).

2.2. Depth Sensing

In the last few years, a new type of Range Imaging cameras has been developed, so called Time-of-Flight (ToF) cameras. It is an active camera sensor which provides dense depth maps in real time; allows acquiring 3D point clouds without any scanning mechanism and from just one point of view at video frame rates.

Figure 2 shows the working principle of ToF which is based on the measurement of an emitted signal by the camera towards the object to be observed, calculating the distance toward the object by means of direct or indirect evaluation of the time since light is emitted by the system until it is received from the scene [2, 3].

Each pixel of the ToF detects both the intensity and the distance, thus provides an intensity, amplitude and range image. The accuracy of the distance for each pixel depends on external interfering factors (i.e. sunlight, extreme climate conditions) and scene properties, i.e., distances, surface orientations, object reflectivity, colour and multiple light reflections. These fluctuations cause noise, but the amplitude image denotes the quality of the 3D measurements; a high amplitude value of a pixel means that its corresponding distance value is more reliable. Therefore, for minimizing noise in a range image acquired in an outdoor environment, the standard filtering is based on the usage of amplitude values, removing pixels with low amplitudes, and the addition of a median filter [4].

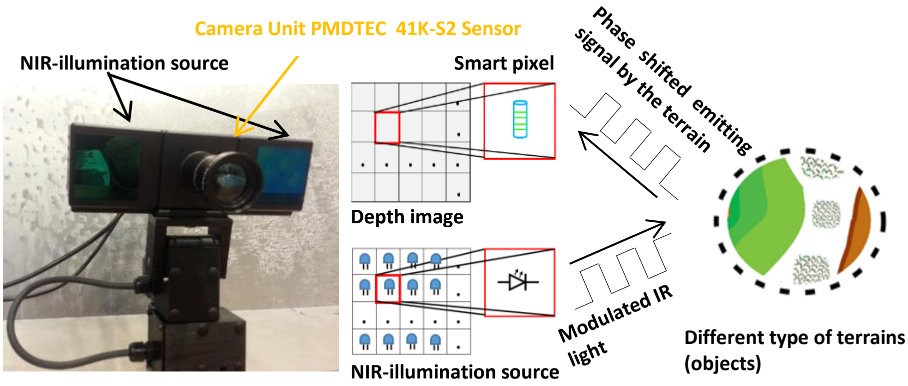

Figure 2: left: setup comprising of a ToF PMD CamCube 3.0 camera on a pan-tilt unit; right: working principle of the PMD CamCube 3.0 camera

One of the advantages of using ToF camera is to simultaneously measure the distance information for each pixel of the ToF. Based on that, some limitations of standard computer vision methods can be overcome, such as the complexity to compute a robust disparity map of stereo cameras, dealing with illumination changes and relative low speed of laser scanning systems. Due to advantages of ToF cameras, they have been used in a wide range of real-time applications with suitability in outdoor scenarios. For this work a PMD CamCube 3.0 camera has been chosen. This model is more robust to sunlight than other ToF cameras [4]. Main drawbacks of the PMD CamCube 3.0 camera are the low 200x200 pixels resolution and noisy depth measurements due to systematic and non-systematic errors. Figure 3 shows the output images provided by the PMD CamCube 3.0 camera in a single shot: 3D information (intensity and range) of the illuminated scene and amplitudes of the returned signal.

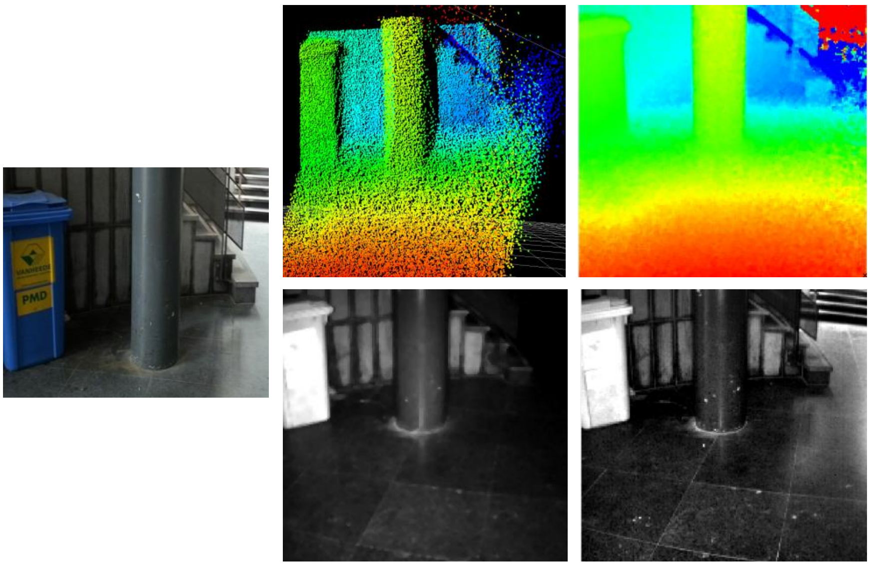

Figure 3: Visualization of data acquired with the PMD CamCube 3.0 camera. On the left side, en example RGB image of an obstacle is shown. The following images, above from left to right, show 3D depth point cloud, depth, below images from left to right, show amplitude and intensity from the observed obstacle scene.

To optimize the field of view of the PMD CamCube 3.0 camera the sensor was mounted in front of the robot with an angle tilted towards the ground plane. The sensor has a modulation distance of 7.5m, so the tilting angle was specifically calculated in order for the sensor not to surpass that distance. This resulted in a field of view between 0m and 7.5m in front of the robot, as shown on Figure 4.

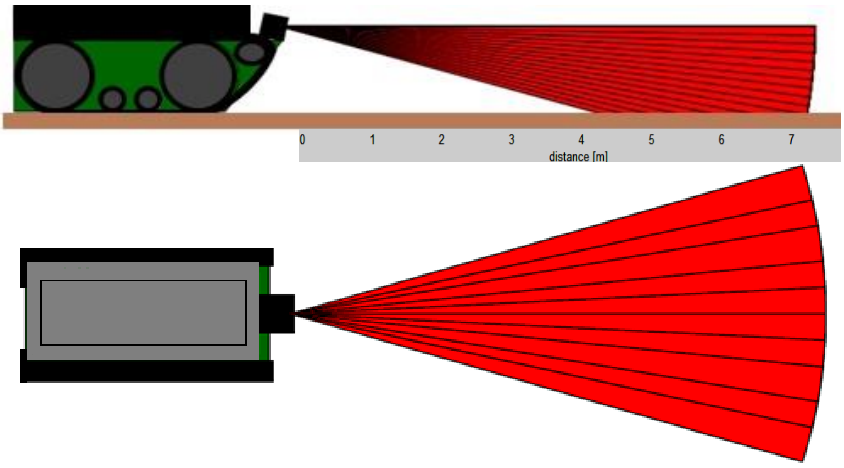

Figure 4: Mounting position and field of view of the PMD CamCube 3.0 camera

3. TERRAIN TRAVERSABILITY ANALYSIS

Autonomous robotic systems operating in unstructured outdoor environments need to estimate the traversability of the terrain in order to navigate safely. Traversability estimation is a challenging problem, as the traversability is a complex function of both the terrain characteristics, such as slopes, vegetation, rocks, etc and the robot mobility characteristics, i.e. locomotion method, wheels, etc. It is thus required to analyse, in real-time, the 3D characteristics of the terrain and pair this data to the robot capabilities. Figure 5 shows the general concept of the terrain traversability estimation using ToF camera.

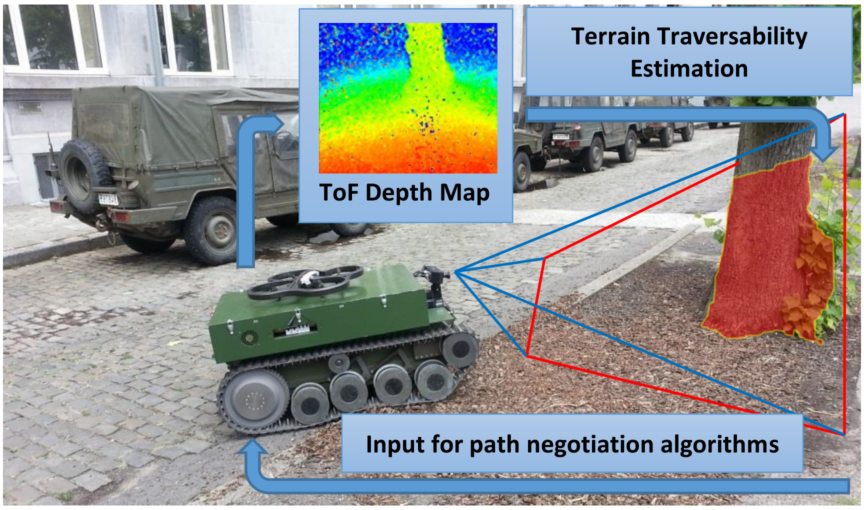

Figure 5: General view of the terrain traversability estimation using ToF PMD camera

The methodology towards ToF based terrain traversability analysis extends the previous work of our group on ToF - based [5] and stereo-based [6, 7] terrain traversability estimation.

Following this strategy, the RGB data stream is segmented to group pixels belonging to the same physical objects. From the Depth data stream, the *v – disparity* [8] is calculated to estimate the ground plane, which leads to a first estimation of the terrain traversability. From this estimation, a number of pixels are selected which have a high probability of belonging to the ground plane (low distance to the estimated ground plane). The mean *a* and *b* colour values in the *Lab colour space* of these pixels are recorded as *c*.

The presented methodology then classifies all image pixels as traversable or not by estimating for each pixel a traversability score which is based upon the analysis of the segmented colour image and the *v-disparity* depth image. For each pixel *i* in the image, the colour difference and the obstacle density in the region where the pixel belongs to are calculated. The obstacle density is here defined as: $\delta_i = \langle o \in A \rangle / \langle A_i \rangle$, where *o* denotes the pixels marked as obstacles (high distance to the estimated ground plane) and A_i denotes the segments to which pixel *i* belongs to. This allows us to define a traversability score as: $\tau_i = \delta_i \, \|c_i - c\|$, which is used for classification. This is done by setting up a dynamic threshold, as a function of the distance measured. An important issue when dealing with data from a TOF camera is the correct assessment of erroneous input data and noise. Therefore, the algorithm automatically detects regions with low intensities and large variances in distance measurements and marks these as "suspicious". Figure 6 shows an example of the terrain classification result. Obstacles are red, well traversable terrain is green and "suspicious" areas (not enough data) are blue. It can be noticed that the classification is correct, as the obstacle (the tree) is well-detected.

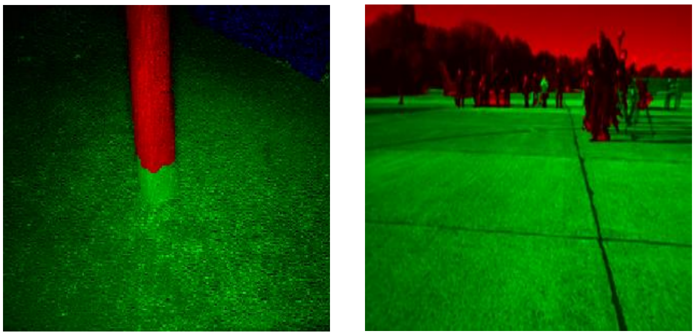

Figure 6: Example of Terrain Traversability Estimation

In the upper right corner (of the left image), there are some problems with foliage giving erroneous reflections (blue area), which is due to the sensor. As the TOF camera orientation is fixed, the traversability estimation can be projected on the ground plane to retrieve a local traversability model, which is used for path negotiation algorithms.

4. SYSTEM TESTING

4.1. Field demonstrations

In this Section, the above mentioned system setup and terrain traversability analysis methodology are evaluated through experimental demonstrations which were performed at the Camp Roi Albert, one of the largest Military bases of the Belgium Defence (located in the city of Marche-en-Famenne, Belgium). Examples of field demonstrations are shown in Figure 7.

Figure 7: Field testing of the proposed system

4.2. Field results

Major issues discovered during the field demonstrations are:

- The tEODor platform has proven its usefulness in dealing with rough terrain, with excellent manoeuvrability and good off-road performance
- The rugged design of the platform makes it capable of handling unfriendly environmental conditions
- Traversability estimation testing is problematic under heavy sunlight conditions and due to the vibration of the tEODor platform (crawler-belt based locomotion and rough terrain)
- Control of the UAV platform due to the weather condition (wind) was problematic but still yielded good results.

5. CONCLUSION

In this article, we have presented the development process of an outdoor mobile robot using a ToF camera sensor and supported with a UAV for terrain traversability analysis. The terrain traversability estimation algorithm is based on our previous work where it classifies all image pixels in the TOF image as traversable or not by estimating for each pixel a traversability score which is based upon the analysis of the 3D (depth data) and 2D (IR data) content of the TOF camera data. This classification result, increasing the environmental situational awareness, can integrate into an autonomous robot control architecture; allowing a mobile robot to navigate (semi) -autonomously in an unstructured outdoor environment.

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