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## **Fusion between a color camera and a TOF camera to improve traversability of agricultural vehicles**

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### **Abstract**

Precision agriculture vehicles need autonomous navigation in cultures to carry out their tasks. The detection of obstacles in crop row is crucial for safe navigation. Lidar devices or Time Of Flight cameras (TOF), allow to obtain geometric data in natural environment. Fusion of those geometric information with a color camera data, improves the identification and discrimination of objects in agricultural cultures. Autonomous agricultural vehicles can use these geometric and colorimetric data in real time, to follow crop rows and detect obstacles while executing various precision agriculture operations, such as monitoring tasks, maintenance or harvesting, for preserving safety, for both vehicle and environment. In our application, a lidar and a TOF camera which detected objects respectively on a plane and in 3D space, were associated with a color camera. Sensors were embedded on a mobile robot. Fusion method consisted to put the lidar and TOF data inside the color image, and make colorimetric and geometric measures on the detected objects (grass, leaf, tree branches), in front of vehicle, for identifying these ones. Traversability operations, tested with a mobile robot in vineyard environment, during crop row tracking operations, consisted to take a decision, according to the size and nature of the detected objects, working under different lighting conditions, and various vegetation levels: the vehicle crossed the object at reduced speed, or it avoided it, or it stopped. Experimentations showed the effectiveness of the approach to detect and identify objects, such as grass or solid obstacles, at various heights from the ground.

**Keywords:** Time Of Flight, sensor fusion, vision, lidar, mobile robot navigation

### **1. Introduction**

The development of Precision Agriculture, with respect to social needs, requires proposing new tool for food production, especially in the fields. Progresses achieved in robotics permitted to consider mobile robots as a promising solution to actually apply new methodologies. Nevertheless, in order to be fully autonomous, such device needs to be accurately and safely controlled, while using relatively low cost sensors. This problem is particularly pregnant considering the obstacle detection and avoidance in natural environment. Complex lidar sensors, such as the celebrated Velodyne could be embedded on vehicles, for terrain classification in agricultural fields (Haselick et al, 2014), or also other 3D laser radar systems for building indoor scenes (Zhang, X et al, 2013), but their cost does not appear to be compatible with the design of agriculture tool. As a consequence, cheapest sensors have to be used, even if they provide less accurate data.

In this paper, the estimation of 3D information required to address obstacles detection and avoidance is investigated through the fusion between on one hand sensors giving geometric information in the environment such as a low cost lidar and a Time Of Flight (TOF) camera and on the other hand a color camera which brings color information on natural objects.

Fusion applications between a lidar and a color camera, is used in various applications, as for example for detecting and identifying by image processing, tree trunks (Shalal et al, 2013), or for autonomous vehicle guidance in cultures (Subramanian et al, 2009) or (Garcia-Alegre et al, 2011). The fusion method improves the recognition of outdoor objects in different illumination conditions and variable weather conditions in dynamic mode, combining the rich and colorful representation provided by images with the planar data given by lidar devices.

In various applications, both kind of sensors (TOF camera and color camera) are used to make measures on agricultural products, like for exemple for plant recognition to achieve robotic weeding (Gai et al, 2015), and for mobile robot locomotion (Joachim et al, 2008). The fusion algorithm proposed aims at controlling an autonomous robot in crop row and detecting the presence of obstacle in order to preserve safety (for both robot and environment). Such a point of view permits to achieve several kind of task, such as environment monitoring tasks, planting, maintenance or harvesting, with accuracy, in agricultural, viticulture or forestry environment, from information of detection, localization and physical characterization obtained on naturel objects, in various cultures.

From these geometric and colorimetric information given by TOF camera, lidar devices and color cameras, in fusion mode, the farmers can achieve agricultural tasks, either in real time, like for example weeding, taking into account the data for each crop, or in differed time, using the recorded databases for a culture. This information can also be used to detect and locate some illnesses in cultures, and also to make comparisons between natural objects in cultures.

## 2. Materials and Methods

### 2.1 Mobile robot and sensors

Sensors used in the experimentations to acquire and compute data, in order to achieve traversability operations in fields, in cultures such as vines, are the following: a lidar Sick model TIMS 551, a giga-ethernet color camera Baumer model VLG 40C and a Time Of Flight camera model PMD-IFM O3M151. These ones were embedded on a mobile robot (Figure 1). The geometric model of the robotic system used for computing position and height of detected natural objects, in front of vehicle, in fields is presented in Figure 2. HTOF and HL design respectively TOF camera and lidar height from ground. D is the distance between the robot and the lowest point (height=0) detected by TOF camera.

In our experimentations, HTOF=630 mm, HL=320 mm and D=3000 mm. Taking into account the vertical angle range of TOF camera (23°), with this system, this camera can see at a distance of 2000 mm from the robot, objects with a height of 220 mm.

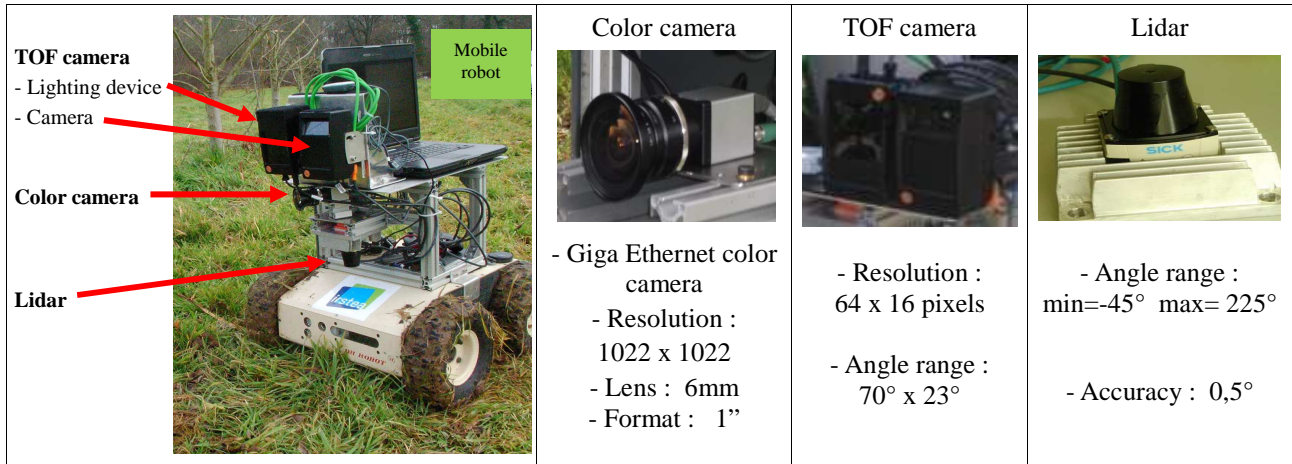


Figure 1. Mobile robot and embedded sensors

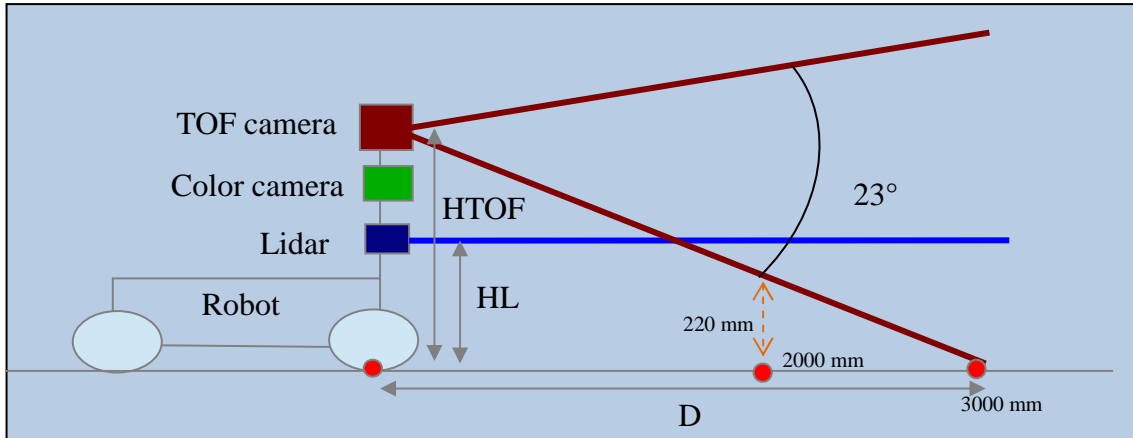
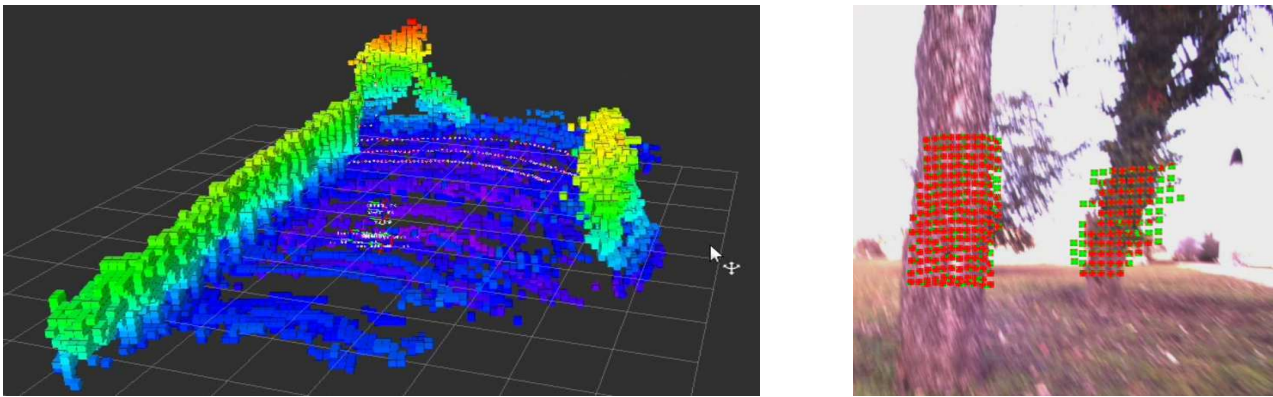


Figure 2. Robot model with sensors for measures

### 2.2 Time Of Flight camera

The TOF camera used is the model IFM PMD O3M151. This one is insensitive to brightness variation, so it can be used for outdoor applications, particularly in agricultural fields, in various lighting conditions, unlike other 3D camera, such as Kinects models, which can only be used in indoor conditions. Comparative studies for TOF cameras were conducted to analyse the measures accuracy, the sensitivity to lighting conditions (Piatti and Rinaudo, 2012). This camera was used in various mobile robotics applications (Hussmann et al, 2009), including the monitoring of borders (Montella and all, 2012). It can be used to produce map scenes both inside and outside, using the fusion mode with a color camera to identify objects. It allows making 3D geometric measures in variable lighting conditions (weakly or strongly sunny). In the field of agricultural machinery, this type of sensor can be used to perform automated steering operations in different cultures to realize various applications such as the monitoring board, the harvesting, recognition swath, self-monitoring line cultures, in particular in the vineyard, to ensure the automatic steering along a vine row.

This sensor can also be used for measure operations on objects located near the sensor and also for security operations near agricultural vehicles for collision prediction and monitoring operations, for autonomous monitoring operations of crop rows, or for traversability operations, focusing on crossing or obstacle avoidance according to the nature and size of the object detected in front of a vehicle. In these operations, the fusion between this TOF camera and a color camera enables to identify detected natural elements with accuracy. Real time image processing algorithms developed can perform geometric and colorimetric measures. Figure 3 shows result examples obtained with this TOF camera, with different lighting conditions in outdoor environment. Figure 3-a presents a 3D environment cartography obtained with TOF camera which will permit to a vehicle to navigate and achieve agriculture tasks in differed time, taking into account TOF data. Figure 3.b presents TOF data inserted by fusion on a color image of detected trees (Red pixels for tree and green pixels for other objects, in environment, using a colorimetric classification method).



(a) (b)  
Figure 3. Outdoor data with IFM PMD O3M151 TOF camera

### 2.3 Sensor Fusion

In our application, two sensor fusion types were considered: a first one between a lidar device and a color camera and a second one between a TOF camera and the same color camera. A first step to achieve these fusion methods between the information given by the three sensors was to conduct a calibration phase which took into account the relative position of sensors embedded on mobile robot and their characteristic parameters, in particular their resolution, accuracy and vision field. Figure 4 shows the method used to insert the geometrical points given by lidar (a) and TOF device (b) inside a color image. For each point, to take into account the inaccurate information provided by lidar and TOF devices, a window was considered around each point on color image. The aim was to detect objects at a distance between 0 and 5 meters from robot, and take a decision in the robot mobility control. The selected window sizes were: 8 x 8 for a lidar point (PL) and 10 x 10 for a TOF camera point (PT). Lidar device gave planar information with high resolution (one point each 0,5°) whereas with TOF camera used, a low resolution image (64 x 16) was obtained.



(a) (b)  
Figure 4. Positioning of lidar (a) and TOF (b) data on color images

Lidar and TOF devices bring complementary information, in our application. Lidar detected all objects situated at a height of HL (lidar height) and TOF device could detect objects at various heights from ground, taking into account the distance between robot and object.

### 2.4 Colorimetric classification and identification

Merging 3D lidar systems with camera was the subject of various works by identifying points or 3D zones in the environment for different classes of color properties (Laible et al., 2013). In this application, point classification by SVM methods (Support Vector Machine) (B. Heran, 2002), is used, focusing on two types of elements: solid objects and grass, working in different lighting conditions. Figure 5 shows the operation SVM corresponding to two types of objects. Solid objects are tree branches or trees (brown or black), and grass-class objects have a dark or light green color, depending in particular of lighting intensity in environment. Pixel identification stage consisted to work in every window around the geometric points detected with the TOF camera (PT) and Lidar (PL), and classify each point using the SVM method. Then computations and measures were applied to count the number of pixels that belonged to solid objects and grass in each color image, in order to take a decision for robot mobility control operations. Figure 6 shows examples of pixel classes corresponding to grass (red window) and solid objects (blue window), selected for the implementation of the classification with the SVM method.

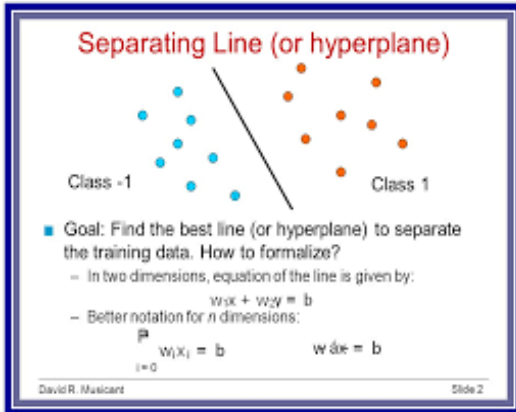


Figure 5. SVM method



Figure 6. Solid objects and grass classes

### 2.5 Traversability in agricultural cultures

TOF cameras can be used for traversability operations in different environments, such as PMD Camcube camera model embedded on farm vehicles, civilian or military (Balta et al., 2013). Detecting solid obstacles such as trees, relatively large is an easy task to achieve with TOF cameras and facilitates autonomous navigation of mobile robots. In our application, solid objects such as branches or trees were considered obstacles to avoid, while grass-type objects were traversable objects. The charts below (Figures 7 and 8) show the various operations carried out to obtain the final decision stage, for a traversability application in a culture. In real time, the mobile robot, according to the data obtained with three sensors (color camera, TOF camera and lidar) adapted its mobility. Grass and solid object were considered separately. In real time, the Grass and Solid point numbers above two height values Gheight and Sheight, respectively for grass and solid objects, were computed. These points could be obtained with lidar or TOF camera. For these point numbers, the maximum value obtained with both sensors was taken into account for traversability decision. The distance values between robot and objects were also considered in this operation. According to the information obtained for grass and solid detected objects, the vehicle could move at normal speed, at reduced speed, must avoid solid objects or must stop, for detected object very near it. Several thresholds values T1...T5 were defined for traversability decision.

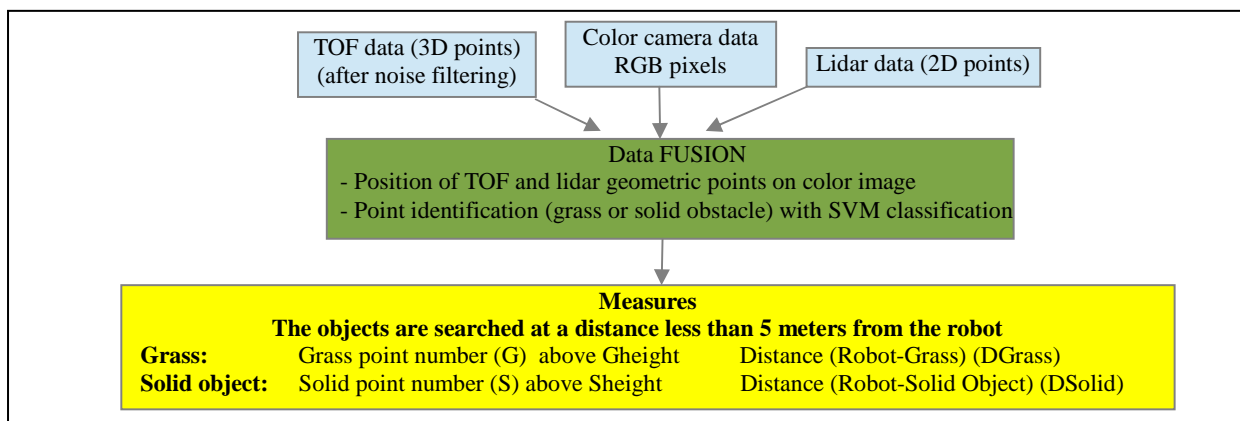


Figure 7. Data acquisition and measures

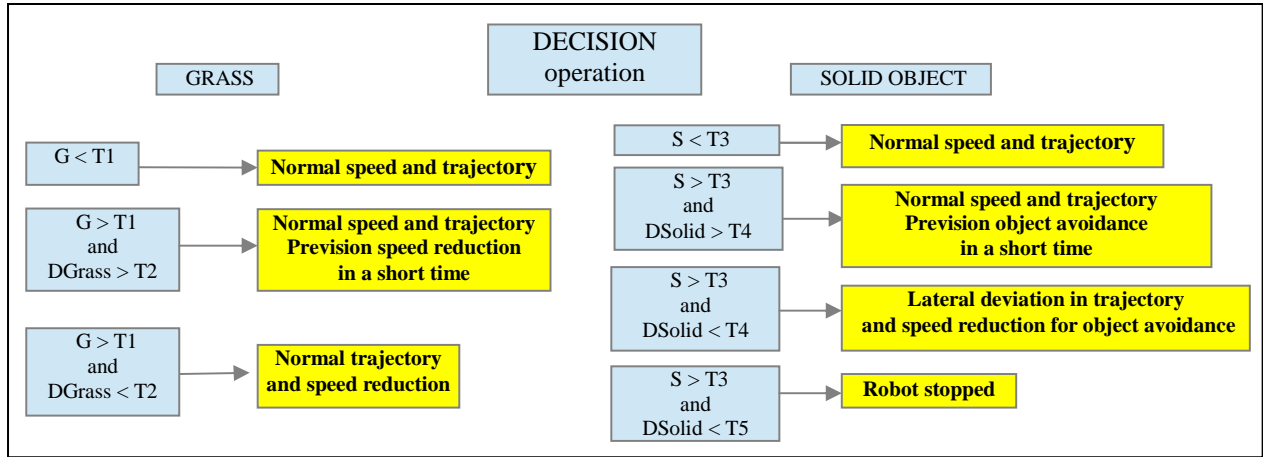


Figure 8. Traversability decisions

### 3. Results and discussion

Different experimentations, to control robot mobility, in cultures containing various grass height and solid obstacles, were achieved, using the developed fusion method, in some fields (Figure 9) with crop raw, particularly in vineyard. In these fields, the aim was to achieve crop raw autonomous tracking, taking into account the presence of grass and solid objects in front of vehicle, to modify speed and trajectory of mobile robot.



Figure 9. Experimentation in fields

For detected object classification, with SVM method, several images corresponding to various lighting intensity in environment, for grass and for solid objects (trees, branches) were considered (Figure 10). Different SVM classification files were achieved to take into account various lighting conditions. According to the mean value of Intensity parameter I (in HIS color space) for each grabbed color image, in real time, one SVM file was chosen automatically, in order to discriminate correctly grass and solid objects. TOF camera and lidar device could work in various lighting conditions.



Figure 10. Selected images for object classification by SVM method

Examples of SVM classification results, to discriminate both object classes, are presented in figure 11, in white and black color, respectively for grass and solid object classes.

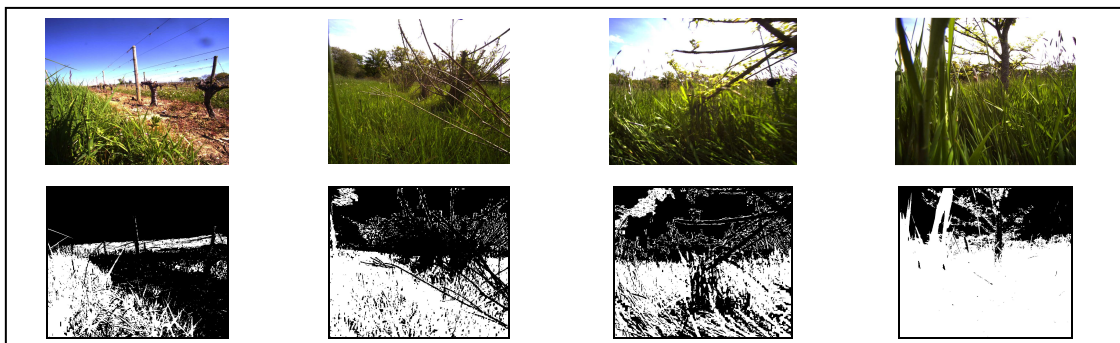


Figure 11. SVM classification result

The crop row detection and navigation through the inter row were achieved using lidar data. This sensor was preliminary used to detect borders and ensured the control of the robot within a row of vegetation, considering data in an angular range between 0 and 90° (right side of image below). The angular range between 90 and 180° (left side) was used to detect objects (solid obstacles like trees or tree branches, and grass) in front of robot (Figure 12).



Figure 12. Lidar data areas for crop raw tracking (tree detection) and object identification for traversability

The fusion method consisted to put the lidar and TOF data inside the color image, and to make some colorimetric and geometric measures on the detected objects in front of the vehicle, for identifying these ones. For each image, the computation of grass and solid point numbers, above respectively of the threshold values chosen for grass points (Gheight) and for solid objects points (Sheight), and the mean distance between robot and these objects, characterized the height and position of these ones. From this information, some decision could be taken in the traversability operations, for crossing or avoiding objects, and in extremes case the robot must stop, if a solid object was in front of the robot, near it. In the experimentations, the aim was to detect grass points above Gheight=320mm (=HL) and Solid points above Sheight=250mm. The threshold value chosen for traversability decision were the following:

$$T1 = 100 \text{ points} \quad T2 = 3 \text{ m} \quad T3 = 100 \text{ points} \quad T4 = 4 \text{ m} \quad T5 = 1 \text{ m}$$

In Figure 13, grass and solid objects detected by lidar device, in front of robot, were put by fusion on color image. Pixel classification results by SVM are presented in red and blue color, respectively for grass and solid objects. Measure results and traversability decisions, taking into account the nature and size of detected objects are presented under each image. For lidar, object were detected at fixed height (HL=320mm from the ground).

<b>Grass (points)</b>	27 < T1	133 > T1	158 > T1
<b>Solid object (points)</b>	2 < T3	8 < T3	12 < T3
<b>Distance (Grass-Robot) (m)</b>	---	3,4 > T2	0,6 < T2
<b>Distance (Solid object-Robot) (m)</b>	---	---	---
<b>Traversability decision</b>	Robot continue moving without any modification in trajectory and speed	Robot continue moving without any modification in trajectory and speed, <b>but will have to reduce speed "in a short time"</b>	Robot continue moving keeping trajectory <b>at reduced speed</b>

Figure 13. Object detection by lidar device and identification by fusion

In Figure 14, grass and solid objects detected by TOF camera, were put by fusion on color image. Pixel classification results by SVM are presented in green and red color, respectively for grass and solid objects.




			
Grass	213 points > T1	156 points > T1	121 points > T1
Solid object	9 points < T3	2 points < T3	328 points > T3
Distance (Grass-Robot)	4,2 meters > T2	2,6 meters < T2	2,9 meters < T2
Distance (Solid object-Robot)	---	---	3,5 meters < T4
<b>Traversability decision</b>	Robot continue moving without any modification in trajectory and speed, <b>but will have to reduce speed “in a short time”</b>	Robot continue moving keeping trajectory <b>at reduced speed</b>	Robot moves <b>at reduced speed and avoids solid object</b> (tree and branches) (lateral deviation)

Figure 14. Object detection by TOF camera and identification by fusion

The application of the fusion method developed to detect and identify objects in front of the vehicle, using the geometric data obtained with the lidar device and the TOF camera, merged with color camera data, has shown that the mobile robot could improve and optimize its mobility, adapting its speed and trajectory, in real time, taking into account, the sensor data, which bring information about the nature and size of objects in front of it. Both grass and solid objects like tree and branches were considered separately. A supposition was made to consider that both object types were not superposed, but sometimes solid objects were hidden by grass. In these experimentations, lidar and TOF camera were embedded on mobile robot with a horizontal position. But depending of the application and of the object type which must be detected, the user could modify the position and orientation of both sensors.

In various fields, lidar devices data were used to detect if grass height was higher than its height from ground (HL). From this information, agricultural vehicles could reduce speed. Planar information given by this sensor was not sufficient to detect with accuracy solid objects (like tree or branches), in order to avoid these ones.

TOF camera, which gave geometric information in 3D space, with low resolution (64x16 pixels) permitted, in various lighting conditions, the detection by fusion of both object types (grass and solid objects), in front of vehicle. From TOF data, solid objects detected could be avoided by vehicle, and grass detection permitted to reduce vehicle speed. The main problem with this sensor was to choose correctly, according to the desired application, its position and orientation, in order to be able to detect objects more or less high, at various distances from vehicle.

#### 4. Conclusions

The proposed fusion method with complementary sensors has been tested on a light mobile robot moving in vineyard, and other cultures, during crop raw automatic tracking operations. The obtained measures by data fusion, in real time, would permit a safe navigation through the field by detecting grass with various height and solid obstacles. The accuracy of sensor data for autonomous navigation and obstacle detection/avoidance has been investigated under different lighting conditions, and using different kind of vegetation.

Two complementary geometric sensors were used in order to detect with accuracy natural objects: lidar sensor could detect objects above its height (320mm in our experimentations) at various distances between vehicle and objects, and TOF camera could detect objects at different heights but this detection depended of the distance. The longer the distance is great plus it can detect objects of low height. Information obtained in real time, by both sensors, was used to detect objects in front of vehicle, at various distances. Despite the low resolution of the TOF camera (64 x 16) objects with different heights from ground and various sizes, such as grass and tree branches, were detected, with accuracy, with this sensor.

With this TOF camera, 3D map, in agricultural fields, could be also performed. This should allow having more accurate information on terrain, and on obstacle geometry, allowing considering traversability maps on areas expected to be crossed by the robot.



This fusion method which gives geometric and colorimetric information can be applied, in various fields, in different agricultural tasks, such as environment monitoring tasks, planting, maintenance or harvesting. For safety operations, for example to detect people, near agricultural vehicles, or in dangerous areas, in order to avoid accidents, the use of a TOF camera associated with a color camera, can be used.

Future works will consist of testing the developed fusion method, taking into account the navigation of the robot on various bumpy soils, with different speeds. Data from an inertial unit (pitch and roll) will be used to correct, in real time, the data of both geometric sensors (lidar and camera TOF), in order to make correct measures on detected objects (grass or solid object), concerning height and size of these objects, and distance between vehicle and object.

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