Multi-sensor fusion method for crop row tracking and traversability operations

Benet Bernard, Lenain Roland

IRSTEA, Clermont-Ferrand, France
Research Unit TSCF, ROMEA Team

bernard.benet@irstea.fr

Pour mieux affirmer ses missions, le Cemagref devient Irstea

www.irstea.fr

1st AXEMA-EurAgEng Conference
Intensive and environmentally friendly agriculture
An opportunity for innovation in machinery and systems in Agriculture

Saturday, February 25th, *1st AXEMA-EurAgEng Conference*, Paris, France

General objective

Controlling an autonomous agricultural vehicle to carry out various tasks in agricultural, vineyard, horticultural, or forestry environment in difficult navigation conditions

(tree branches) in front of vehicle, many grass on ground, high vegetation level

TASKS: planting, maintenance, harvesting

Two main operations:

Autonomous **Crop row tracking**

Traversability: crossing or avoiding obstacles in front of vehicle







Autonomous crop row tracking for weeding operations

Mechanical weeding

Thermical weeding

French Project Adap2E (ANR)

Autonomous navigation in vineyard environment

Saturday, February 25th, *1st AXEMA-EurAgEng Conference*, Paris, France

CROP ROW TRACKING OPERATION

Autonomous navigation in different crops

Various vegetation level, various lighting conditions, obstacles (grass, solid objects) in front of vehicle, with mudy and bumpy soils

Crop rows

What kind of sensors for auto tracking of crop rows ?

GPS (absolute localisation in the fields)

-Path recording (GPS points (latitude and longitude) near crop lines.
-From learned paths, the vehicle follows the crop rows.

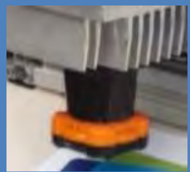
However, if the GPS sensor doesn't work correctly (loss of GPS signal, the vehicle may deviate from its desired path.

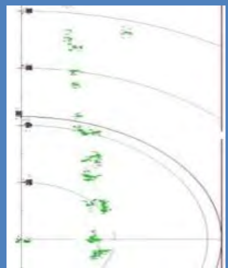
What kind of sensors for auto tracking of crop rows ?

Relative localisation in the fields

Camera

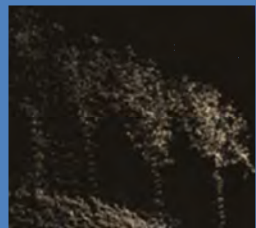
LiDAR 2D (1 layer)





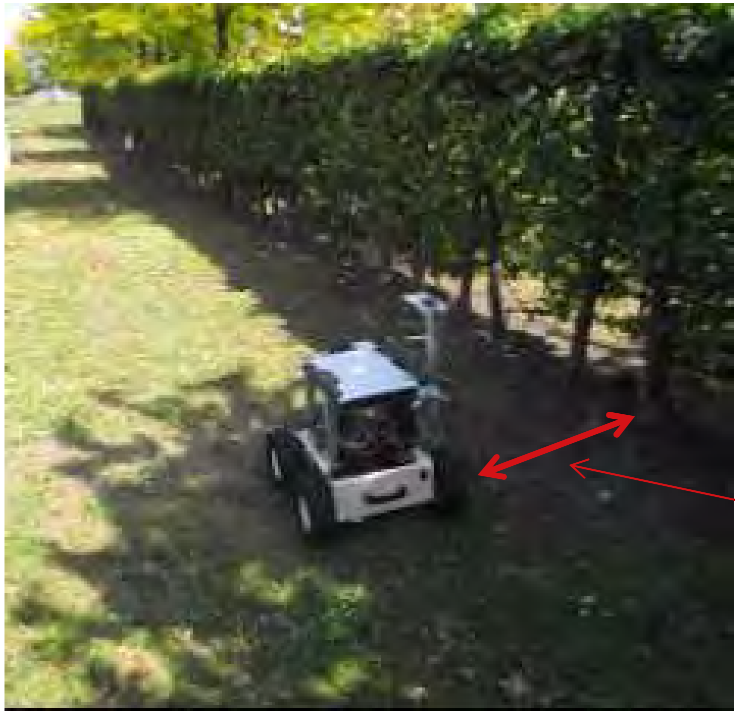
LiDAR (32 layers)

TOF Camera 3D



What kind of sensors for auto tracking of crop rows ?

Camera or LiDAR devices (relative localisation between vehicle and crop line)



Lateral deviation

Camera (Artificial Vision)

Advantages

- Many information 2D on vine trunk
- Make differences between objects (vine trunks – leaf or grass)
- Only one camera is sufficient to locate in 3D environment the vine trunks (lowest points on the soil) on a flat ground

Camera (Artificial Vision)

Disadvantages:

- **Sensitive to lighting variations**

- **Sensitive to shadow zone near vine trunks**

Artificial vision method for auto tracking of vine rows

- Automatic detection and localisation of lowest points of vine trunks
- **No grass near tree trunks**
- Linear regression to obtain the vine trunk line
- Referenced-vision command operations applied to control a vehicle which follows the vine lines and realize viticultural tasks

Original image

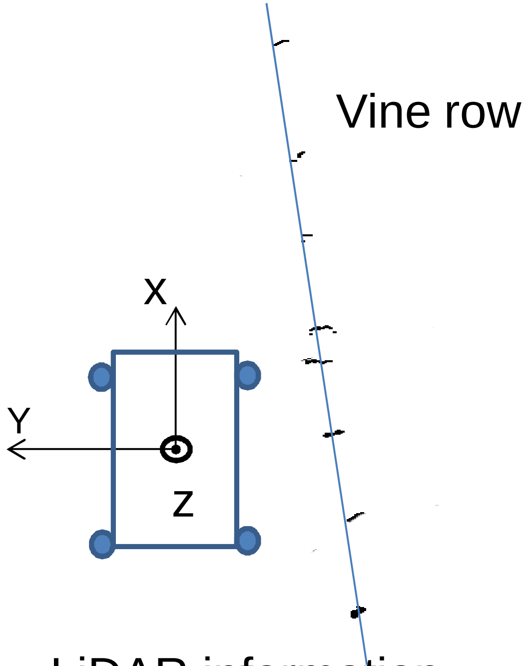
Final image

LiDAR devices

Advantages:

- One LiDAR gives information of the relative position between vehicle and vine trunks. It is « easy » to follow the crop line.
- Not sensitive to lighting variations

Vine image



LiDAR information

LiDAR devices

Disadvantages:

- It is necessary to define the right height of the sensor from ground, to detect and locate with accuracy vine trunks (various sizes and shapes) and avoid noise (leaves, grass)
- Vibrations: detection of ground points instead of tree trunks
- Don’t make differences between objects (trunk, leaf or grass)

LiDAR height ?

Solution for <u>Crop row tracking operation</u>

FUSION LiDAR / Camera

- LiDAR for detecting points
- Camera to discriminate LiDAR Points and identify crop points (tree trunks) which will be followed by agricultural vehicle

TRAVERSABILITY operation

Presence of solid objects
(tree branches)
in front of vehicule

Vehicle must reduce speed
- They must avoid obstacle
if solid object are very big or very high

- They can cross small solid obstacle

Presence of grass
in front of vehicule

Vehicle must cross obstacle at reduced speed
(speed can be adapted to **grass height)**

Without obstacle

With obstacle (grass or solid object)

Solution for Traversability operation

FUSION (LiDAR or TOF camera) / Camera

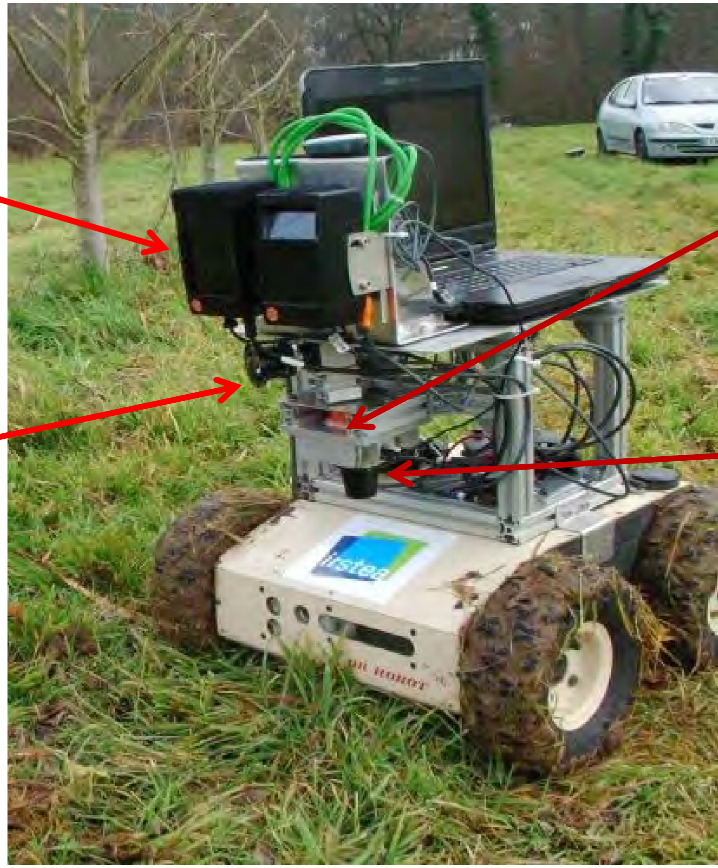
- LiDAR or TOF for detecting points (geometric data)

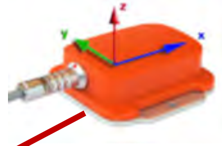
- Camera to discriminate LiDAR or TOF points and identify obstacle (nature and size) in front of vehicle

Light mobile robot and sensors for crop row tracking and traversability operations with sensor fusion

TOF camera (IFM)
- Resolution : 64 x 16 pixels
- Angle range : 70° x 23°

Giga Ethernet color camera (Baumer**)**
- Resolution : 1022 x 1022
- Lens : 6mm
- Format : 1”





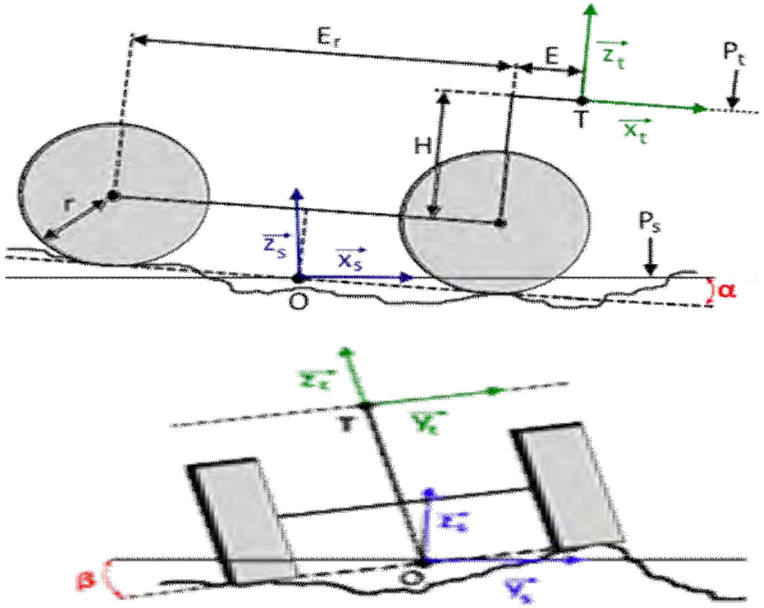
IMU (Xsens)

LiDAR (Sick)
- Angle range : 270°
- Accuracy : 0,5°

SENSOR FUSION

- TOF camera
- Color camera
- LiDAR
- IMU

Robot model with IMU data



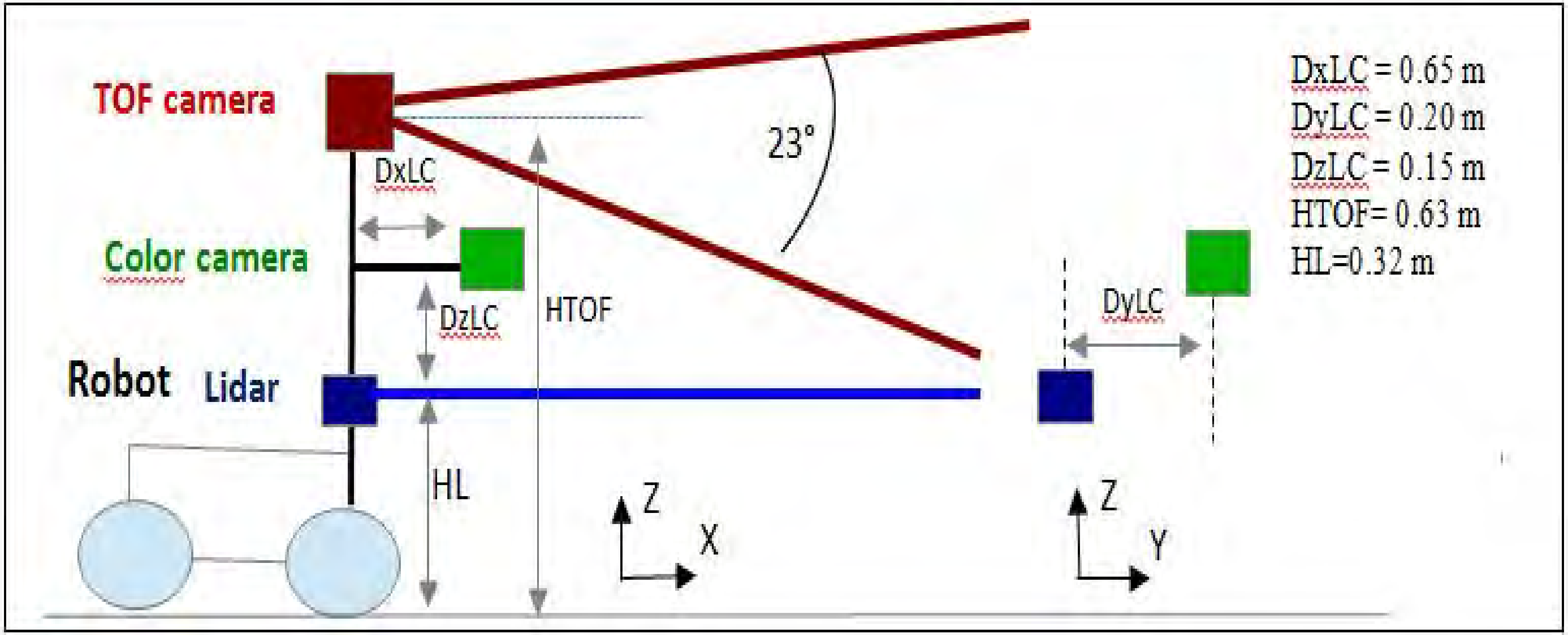
With - H = 0.19 m (LiDAR height / axis of the wheels)
- E = 0.01 m (distance between the LiDAR and the front axle)
- Er = 0.35 m (distance between the centers of the wheels)
- r = 0.13 m (wheel radius)

- IMU data: **roll (α) and pitch (β) angles**

Model for mobile robot and sensors

System calibration

(extrinsec parameters in the color camera model)



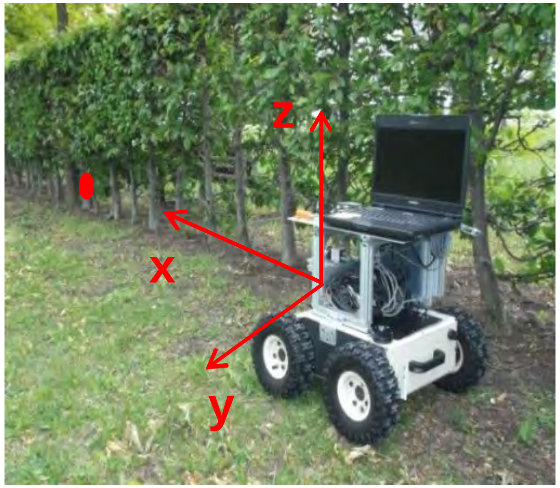
FUSION IMU / (LiDAR or TOF)

(ρ, Θ, α, β) ⟶ $P_{\text{LiDAR Corrected}}$ (x,y,z)

LiDAR IMU

(x, y, z α, β) ⟶ $P_{\text{TOF Corrected}}$ (x,y,z)

TOF IMU



For LiDAR points

$$
\begin{aligned}
x &= \rho.\cos(\theta).\cos(\beta) - (E + 0{,}5.E_r).\cos(\beta) + (r + H).\cos(\alpha).\sin(\beta) \\
y &= \rho.\sin(\theta).\cos(\alpha) - (r + H).\sin(\alpha).\cos(\beta) \\
z &= \rho.(\sin(\theta).\sin(\alpha) - \cos(\theta).\sin(\beta)) - (E + 0{,}5.E_r).\sin(\beta) + (r + H).\cos(\alpha).\cos(\beta)
\end{aligned}
$$

All points outside the crop point research area are eliminated (example z<10 cm)

Grass height parameter = 10 cm

Image, camera and world landmarks

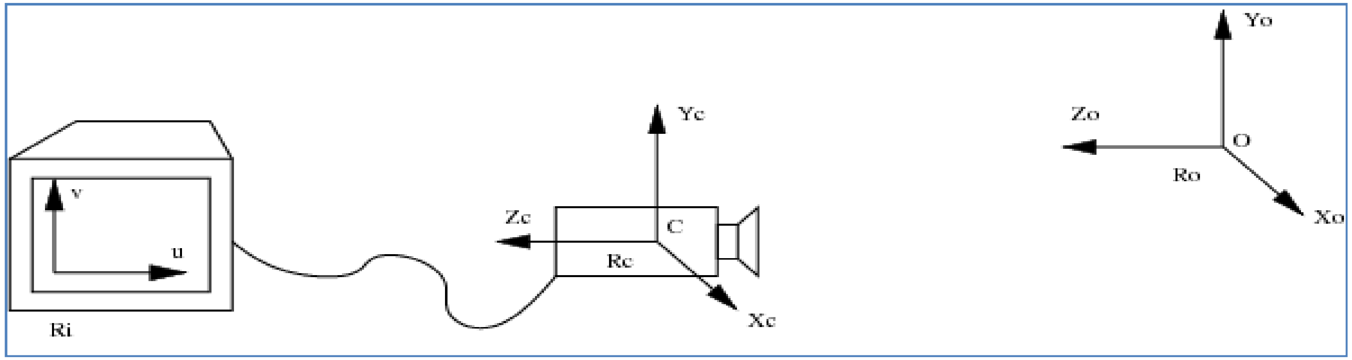


Image Camera World

Color camera model: intrinsec and extrinsec parameters

$$\begin{pmatrix} su \\ sv \\ s \end{pmatrix} = \begin{bmatrix} k_u & s_{uv} & c_u \\ 0 & k_v & c_v \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} & R_{3\times 3} & & t_x \\ & & & t_y \\ & & & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

Intrinsecs parameters Extrinsecs parameters

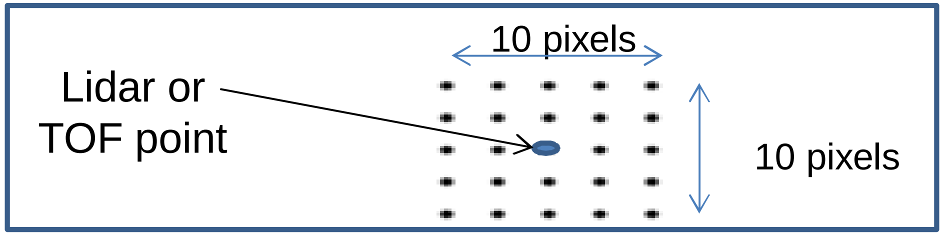
FUSION Camera / (LiDAR or TOF)

FUSION Camera / (LiDAR or TOF)

FUSION (LIDAR AND COLOR CAMERA)
LiDAR points inside image

FUSION (TOF AND COLOR CAMERA)
TOF points inside image

To take into account resolution difference between sensors



For each point, 100 pixels on color image are computed, for identification operation.

PIXEL CLASSIFICATION

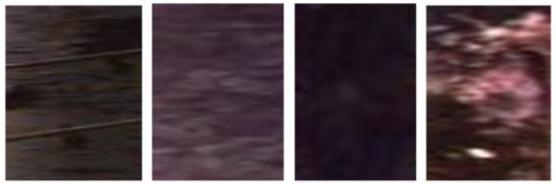
Discrimination between 2 classes (**Grass or Leaf) and (Solid object (crops, tree branches))** in various lighting conditions, with SVM method

PIXEL CLASSIFICATION

Discrimination between 2 classes (**Grass or Leaf)**
and (Solid object (crops, tree branches))
in various lighting conditions

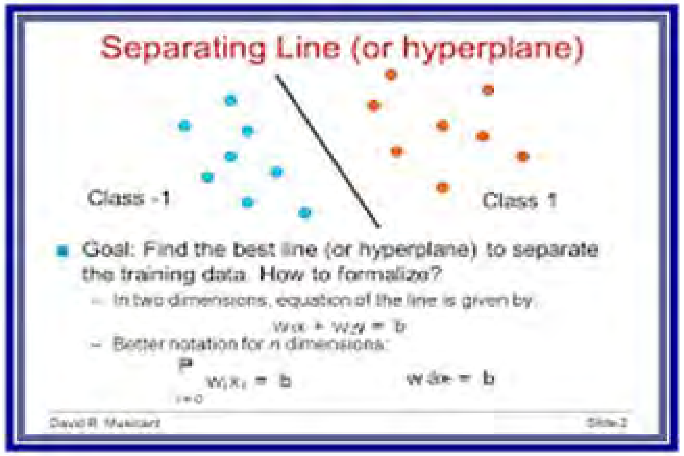
Images for both classes

Grass classes

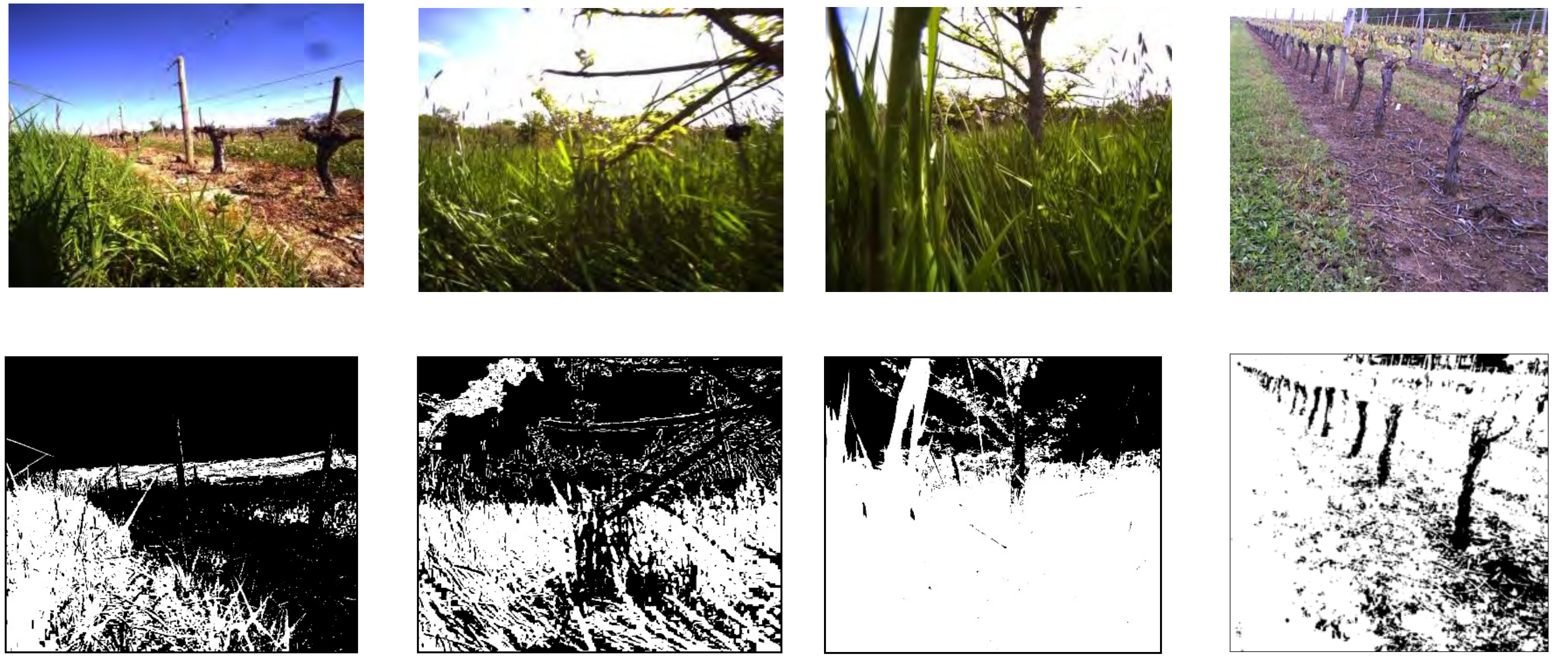


Solid object classes (crops, branches)

SVM Method



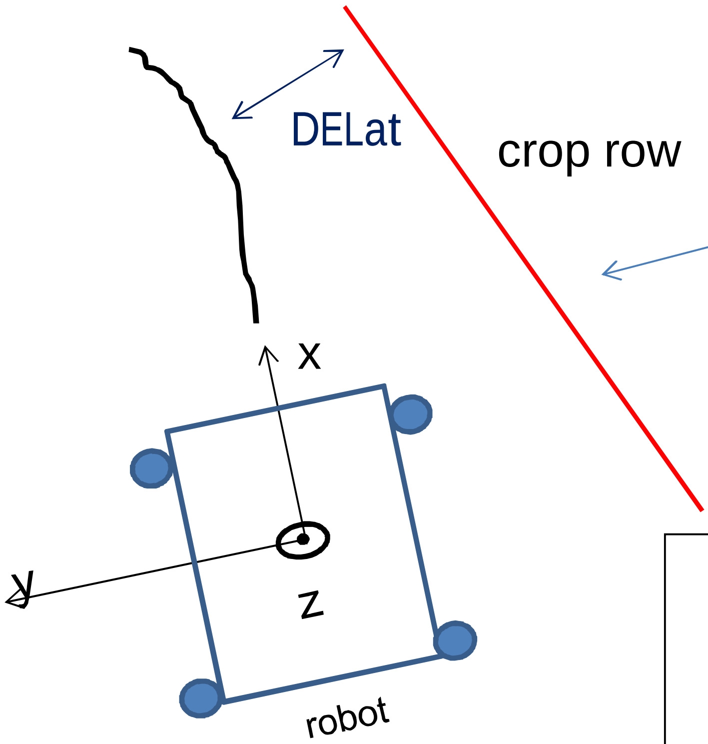
CLASSIFICATION RESULTS



White = Grass color   Black = Solid object color

CROP ROW TRACKING OPERATION

Crop row tracking operation



From LiDAR data

$$Y = m\,X + p$$

(in robot landmark)

Robot Command (Speed and Angle)
for crop row tracking

with the objective:

Y = lateral deviation desired (DElat)

Fusion LiDAR and Color camera

LiDAR information for one point **(ρ, ϴ)**

In the robot landmark

$P_{\text{LiDAR corrected}}$ (**x,y,z**) (with IMU data)

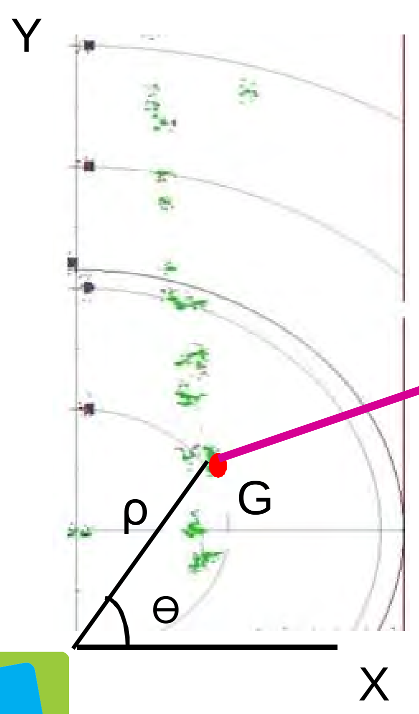
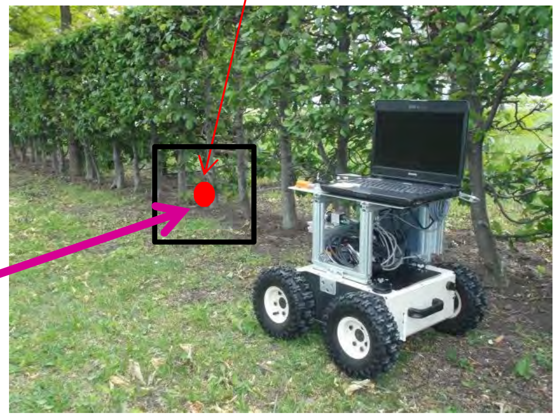
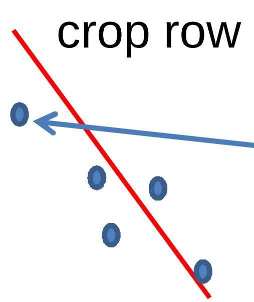


Image pixel I(u,v)

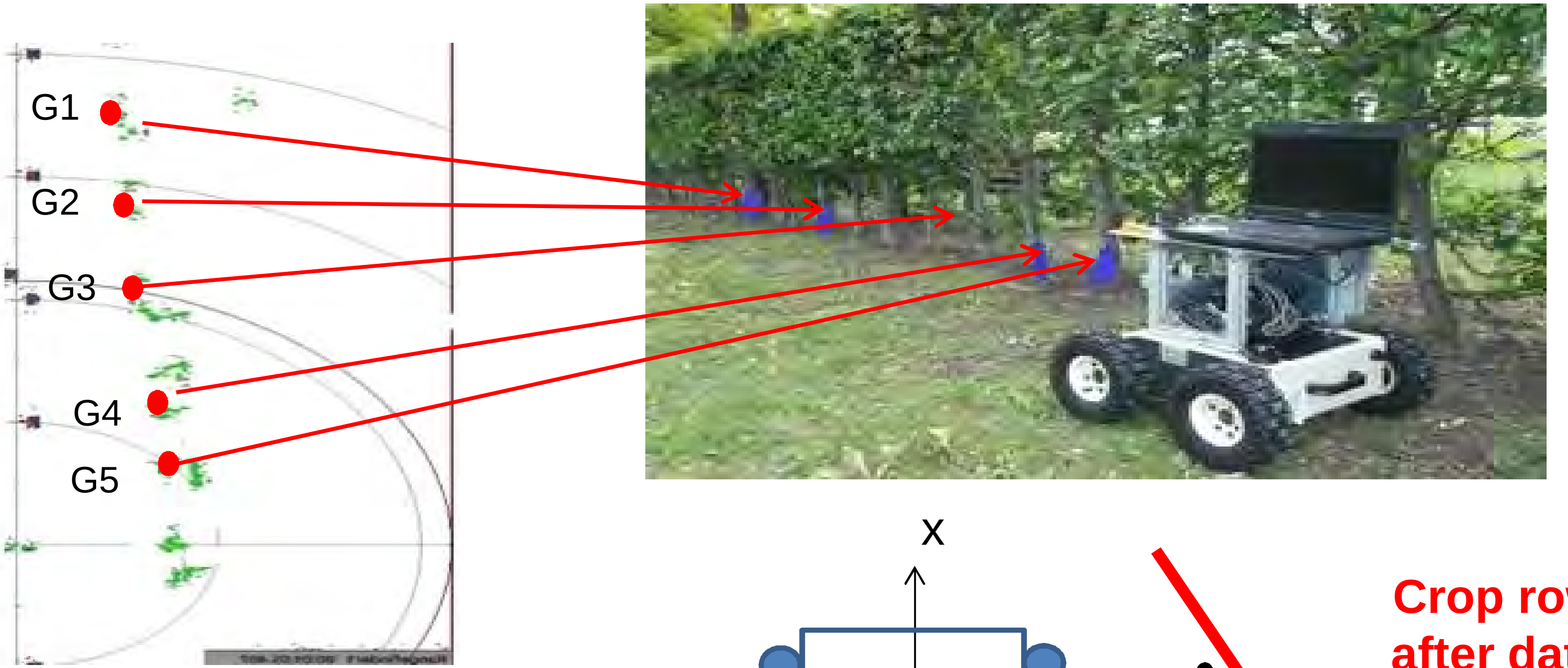


SVM method around pixel I:
Mean color computation (windows 10x10 pixels)

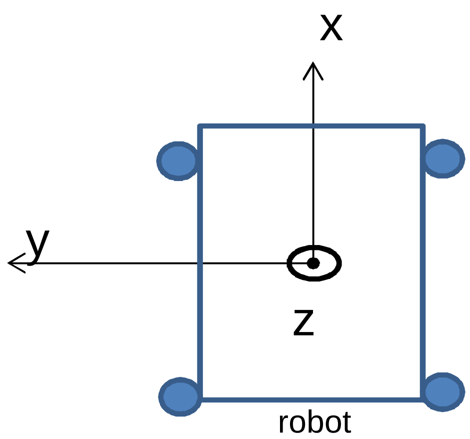
Identification
Crop point detected
or
No detection

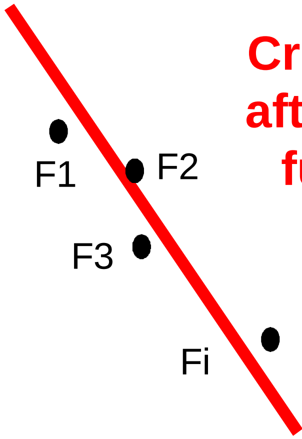


Fusion LiDAR and Color camera



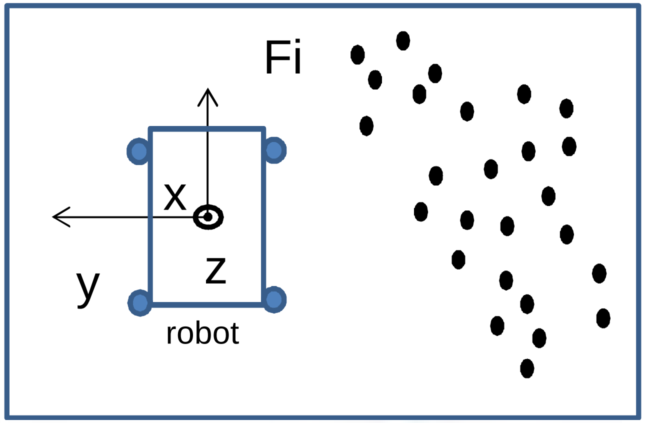
G1 → F1
G2 → F2
G3
G4 → F3
G5 → F4
… …
Gi Fi
…



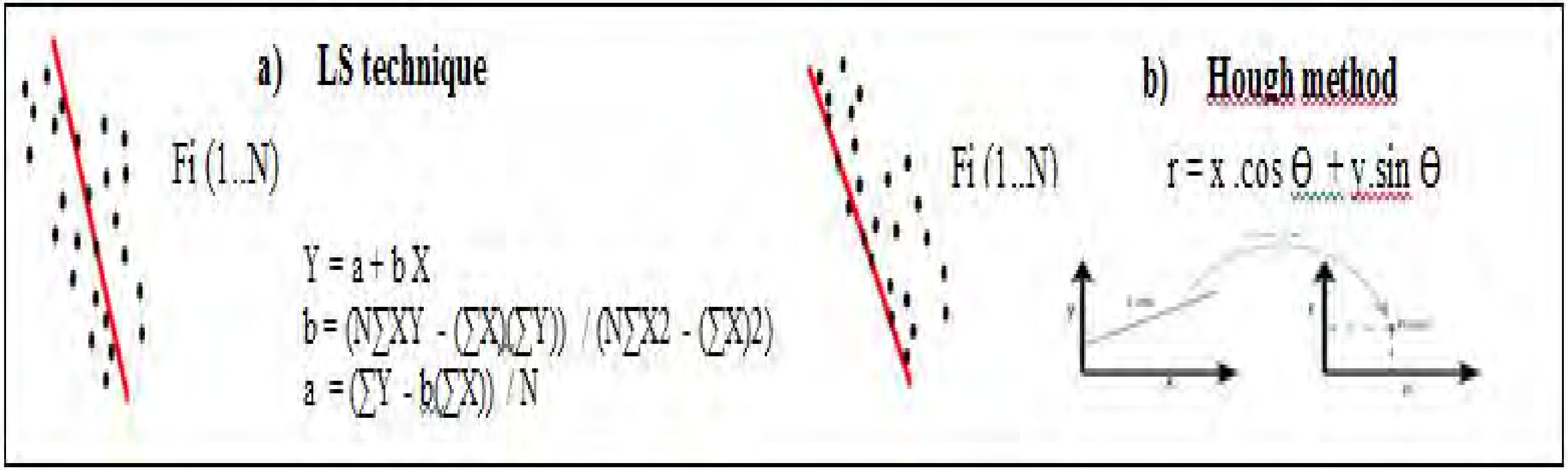


Crop row after data fusion

How to obtain crop row geometric information ?

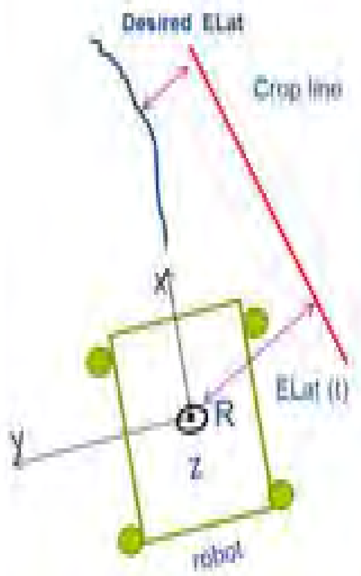


Fi (xi,yi)



Robot control for crop row tracking

Crop line $Y = a + b X$ (perception)



Robot Jaguar control/command for crop row tracking operation

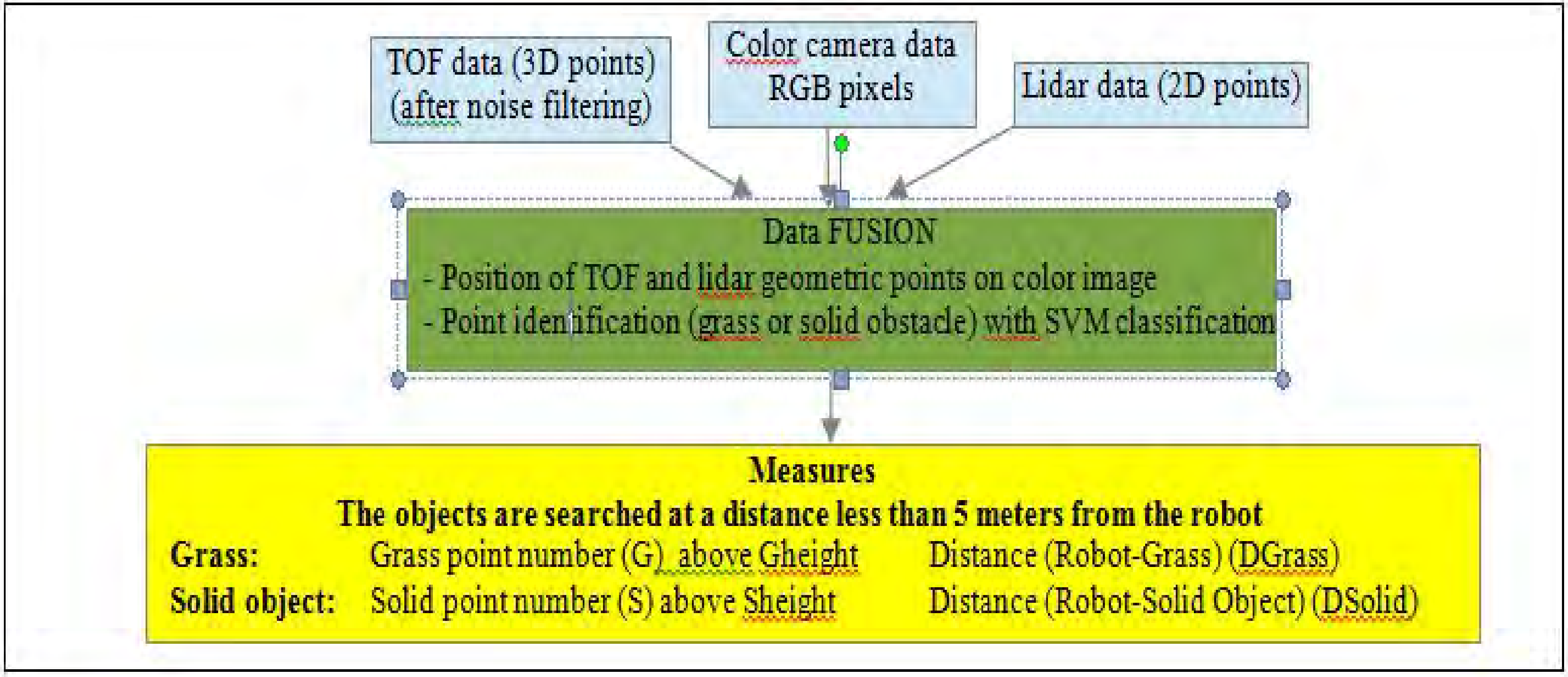
Lateral command: ELat (t) = DELat - distance (R - Crop line) = DELat - (abs(a) / sqrt(b^2+1))

Angular command: Course deviation (t) = PI/2 - atan(-1/b)

Time filtering: ELat (t) = c x ELat (t) + (1-c) x ELat (t-1) c € [0;1]

TRAVERSABILITY OPERATION

SENSOR DATA ACQUISITION, FUSION AND MEASURES

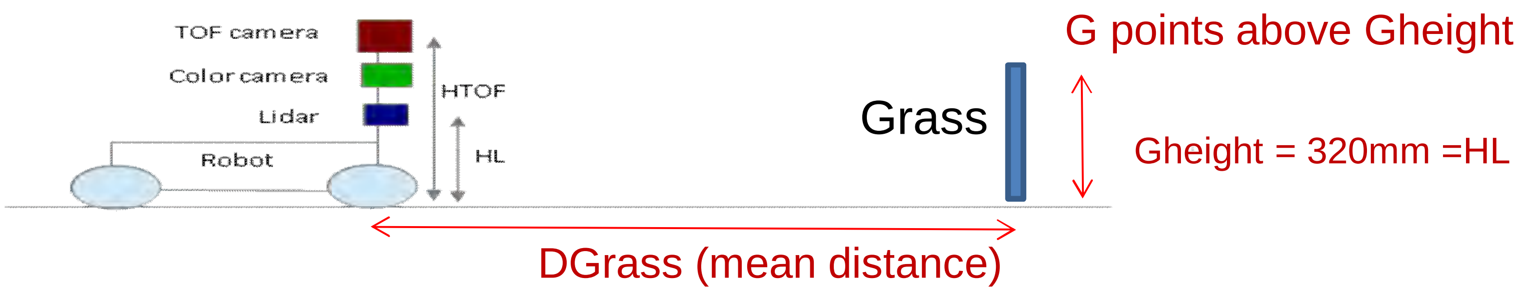


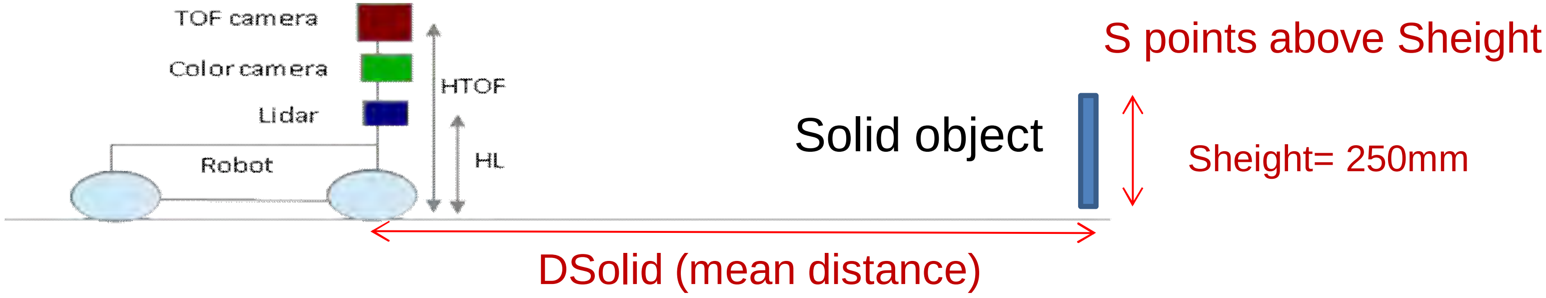
SENSOR DATA ACQUISITION, FUSION AND MEASURES

Measures

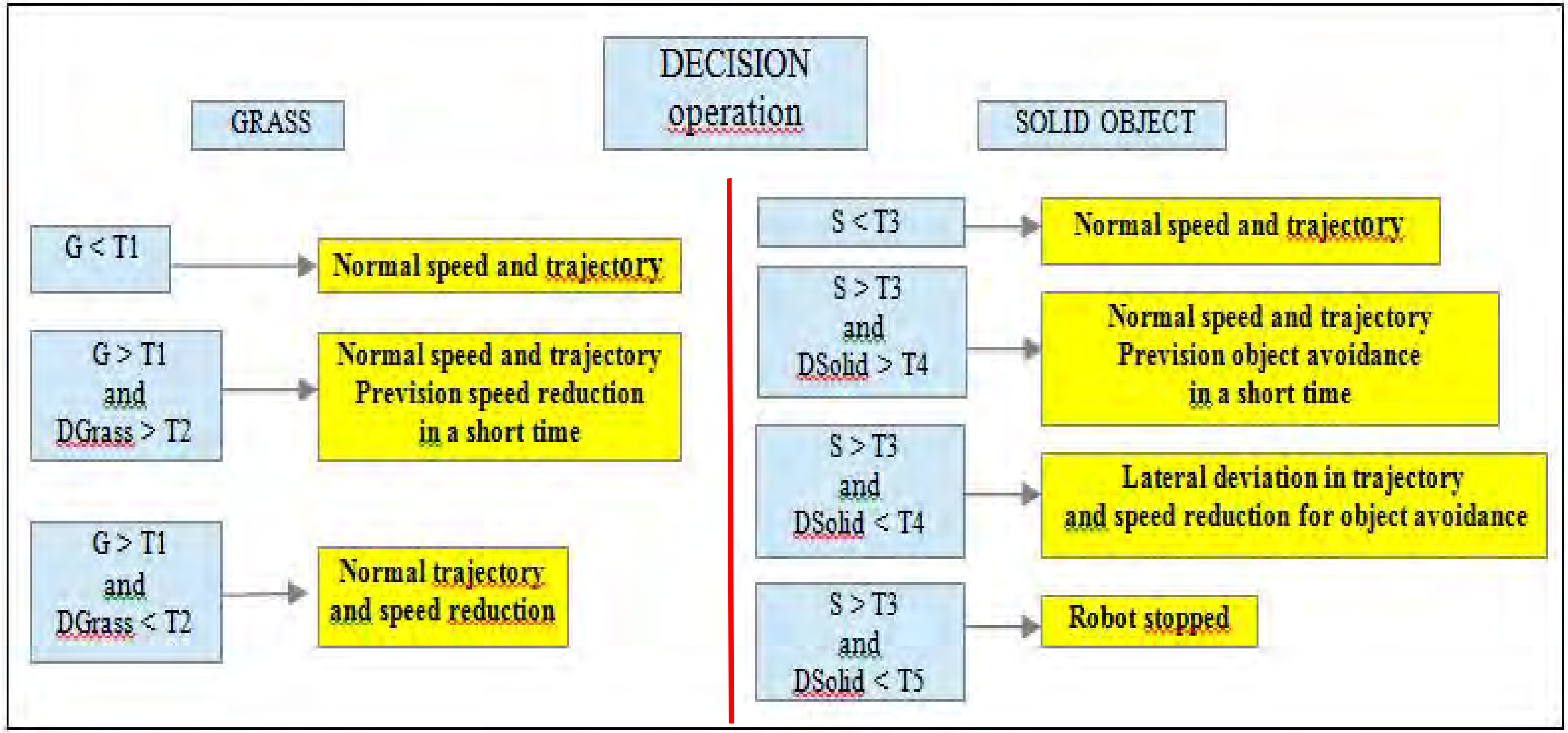
The objects are searched at a distance less than 5 meters from the robot

Grass:	Grass point number (G) above Gheight	Distance (Robot-Grass) (DGrass)
Solid object:	Solid point number (S) above Sheight	Distance (Robot-Solid Object) (DSolid)





TRAVERSABILITY DECISION



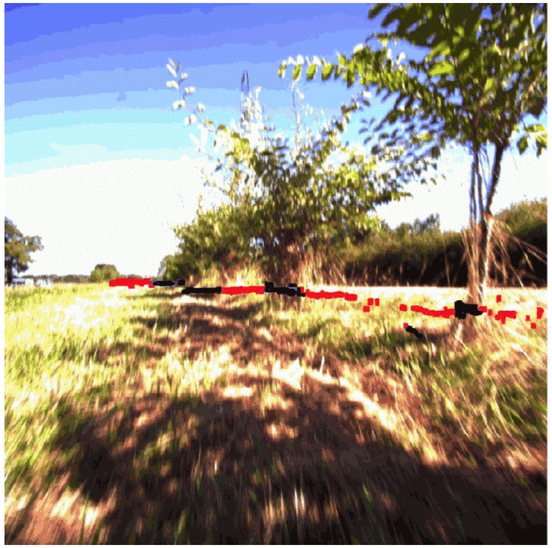
Threshold values: T1 = 100 points T2 = 3 m T3 = 100 points T4 = 4 m T5 = 1 m

RESULTS

CROP ROW TRACKING OPERATION

Saturday, February 25th, *1st AXEMA-EurAgEng Conference*, Paris, France

FUSION RESULT (LiDAR/Camera)

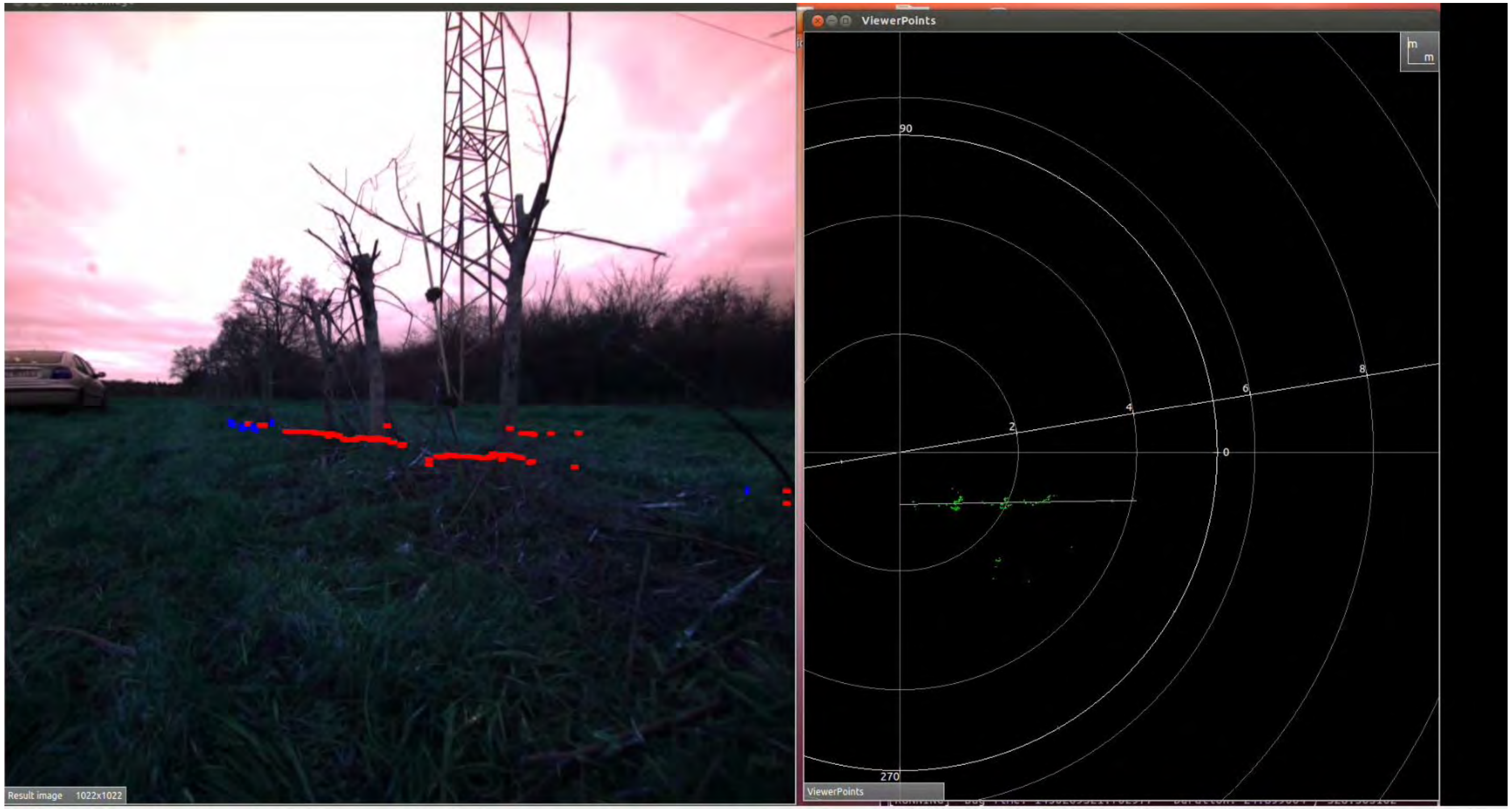


FUSION RESULT (LiDAR/Camera)

Grass
Trunks

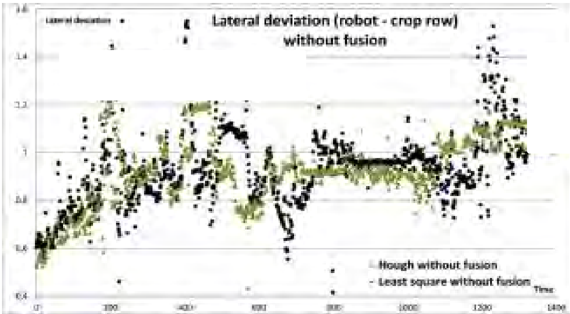
FUSION RESULT (LiDAR/Camera)

Grass
Trunks

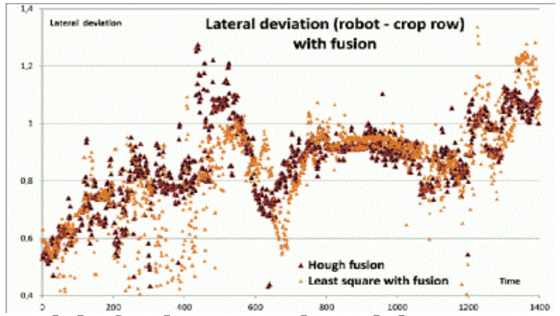


Comparison between LS technique and Hough method

Manual navigation (with joystick)



Without fusion mode (LiDAR only)



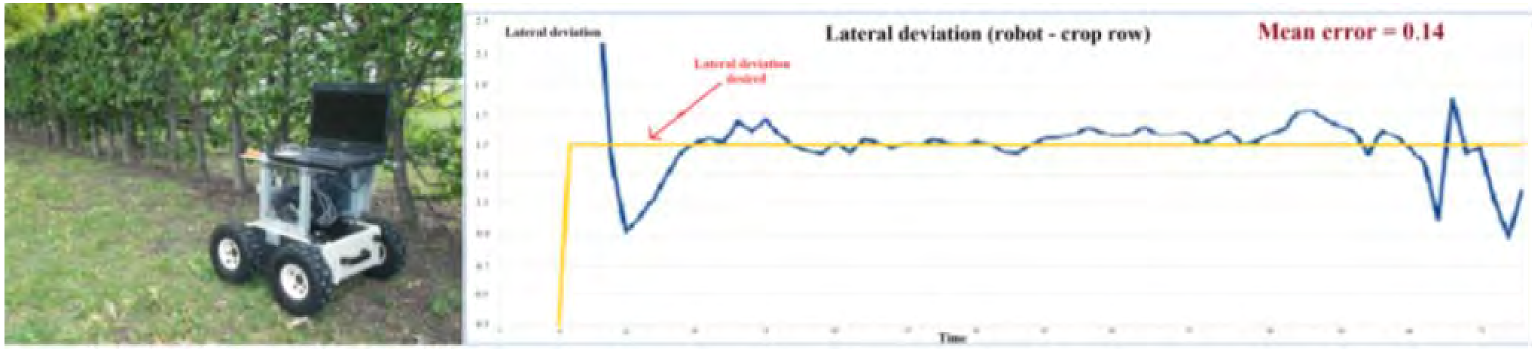
With fusion mode with camera

	Without fusion		With fusion (camera)	
	Hough method	LS technique	Hough method	LS technique
Standard deviation of lateral deviation	**0.15 m**	**0.20 m**	**0.14 m**	**0.17 m**

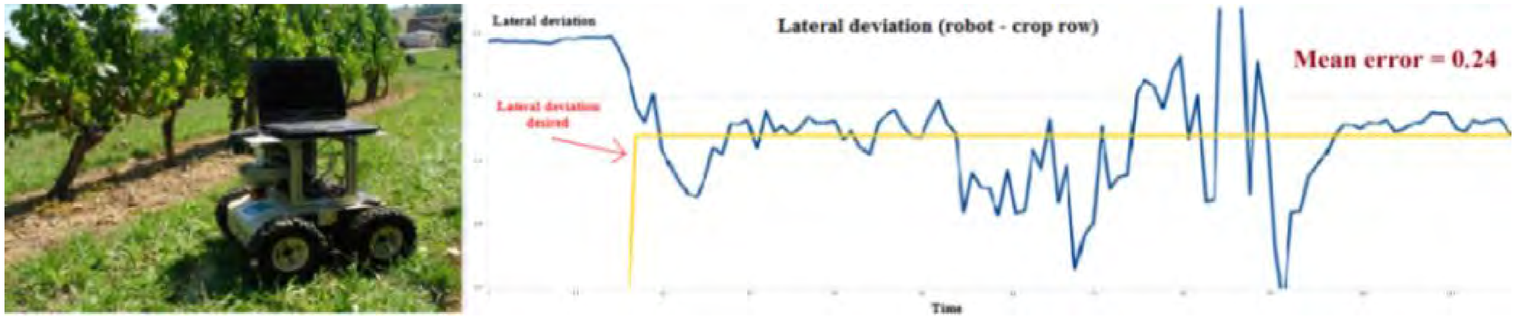
Hough method with fusion (LiDAR, IMU and Camera) is more stable than LS technique, to detect and follow crop rows, with reduced oscillations in navigation

Crop row tracking on soil without and with perturbations (mud, bumps)

Control/command speed: 1m.s^{-1} , Coefficient c for temporal filtering: 0.8, Desired lateral deviation: 1.5 m.

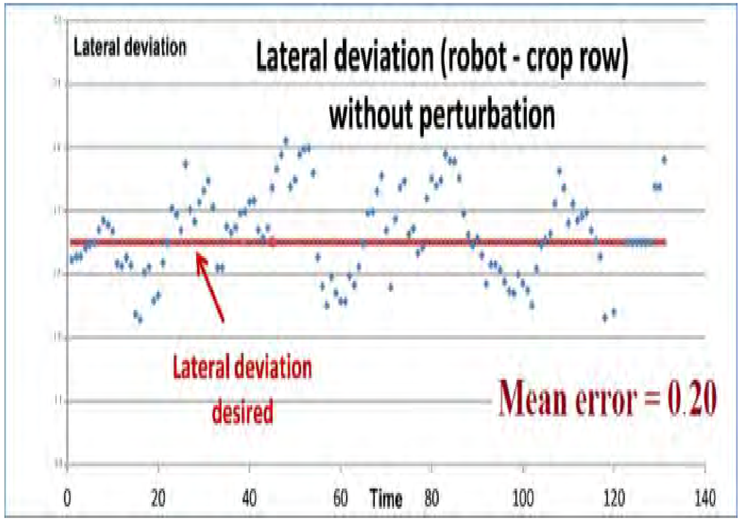


Without perturbation

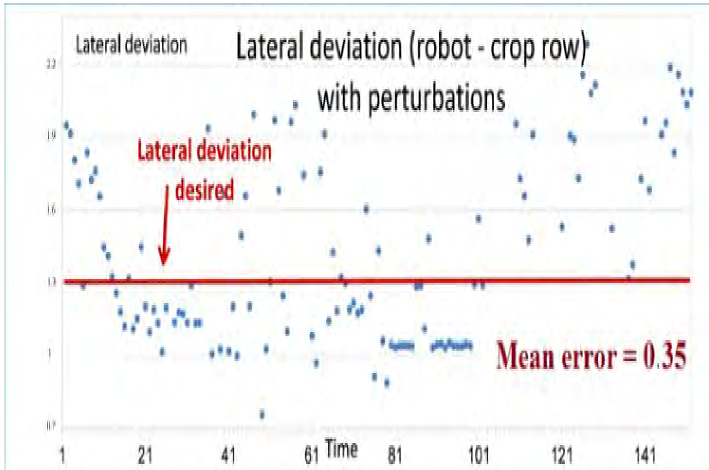


With perturbations (bump, mud)

Speed influence on crop row tracking accuracy



Without soil perturbation



With soil perturbation (bumps, mud)

Control/command speed: 1.5 $m.s^{-1}$

Crop row tracking operations
Accuracy results

MEAN ERROR FOR LATERAL DEVIATION with fusion	Speed 1 m.s-1	Speed 1.5 m.s-1
Without perturbation	**0.14 m**	**0.20 m**
With perturbations	**0.24 m**	**0.35 m**

General results

Mean error between **0.1 and 0.4m**

Expérimentations Results

Control speed: 1m.s^{-1} , Coefficient c for temporal filtering: 0.8,
Desired lateral deviation: 1.5 m, Hough method

TRAVERSABILITY

EXPERIMENTATION – RESULTS

Vineyard – Other crops




FUSION RESULT and TRAVERSABILITY DECISION

Color camera and Lidar

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

FUSION RESULT and TRAVERSABILITY DECISION

Color camera and TOF camera

Grass points Solid object points (tree, branches)			
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
Traversability decision	Robot continue moving without any modification in trajectory and speed, **but will have to reduce speed "in a short time"**	Robot continue moving keeping trajectory **at reduced speed**	Robot moves **at reduced speed** and **avoids solid object** (tree and branches) (lateral deviation)

FUSION RESULT WITH LIDAR TRAVERSABILITY DECISION

Color camera and Lidar - Vineyard environment

Grass
Solid object

FUSION RESULT WITH LIDAR TRAVERSABILITY DECISION

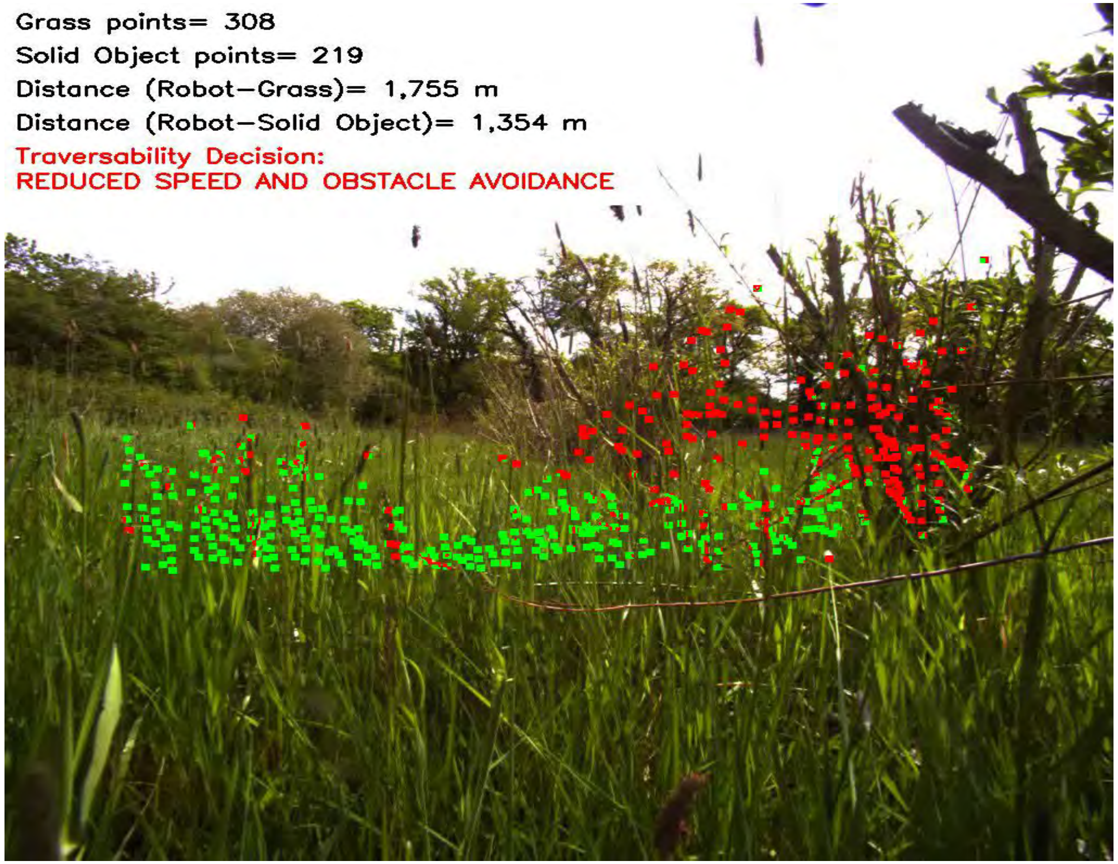
Color camera and Lidar - Vineyard environment

Grass
Solid object

FUSION RESULT WITH TOF CAMERA TRAVERSABILITY DECISION

Color camera and TOF camera

Grass
Solid object



FUSION RESULT WITH TOF CAMERA TRAVERSABILITY DECISION

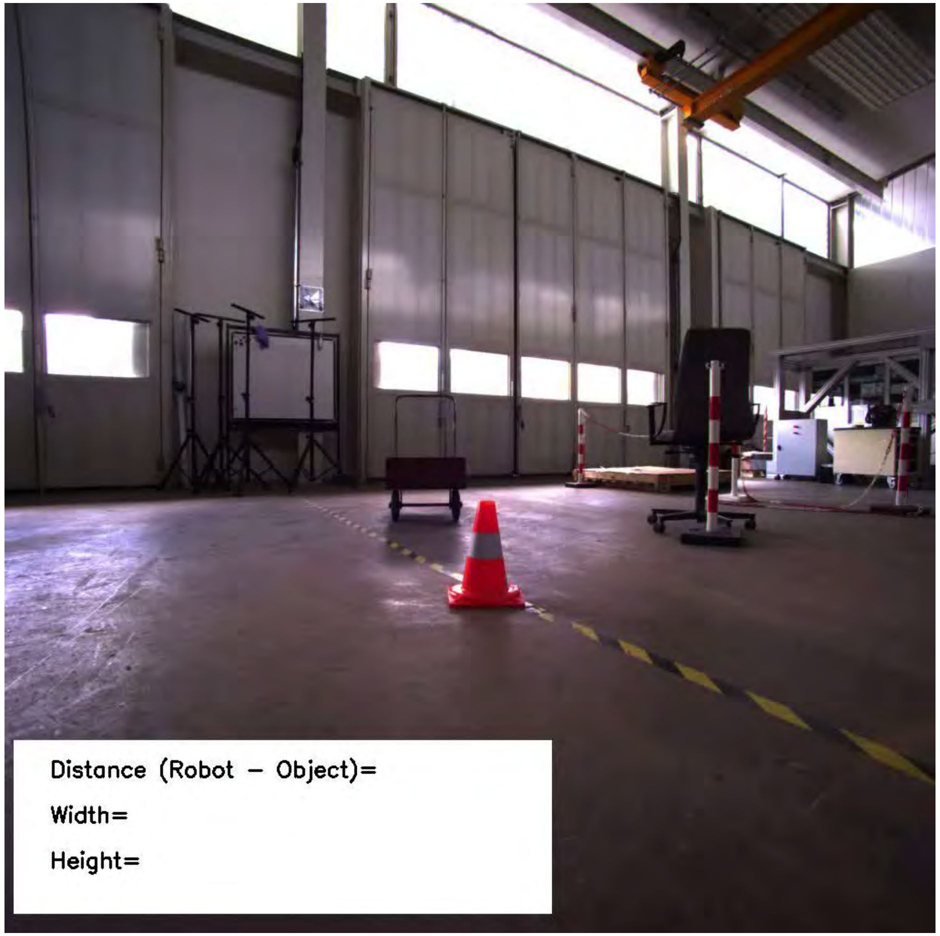
Solid object detection

Solid object

SAFETY OPERATIONS
FUSION RESULT WITH TOF CAMERA
People detection near agricultural vehicles

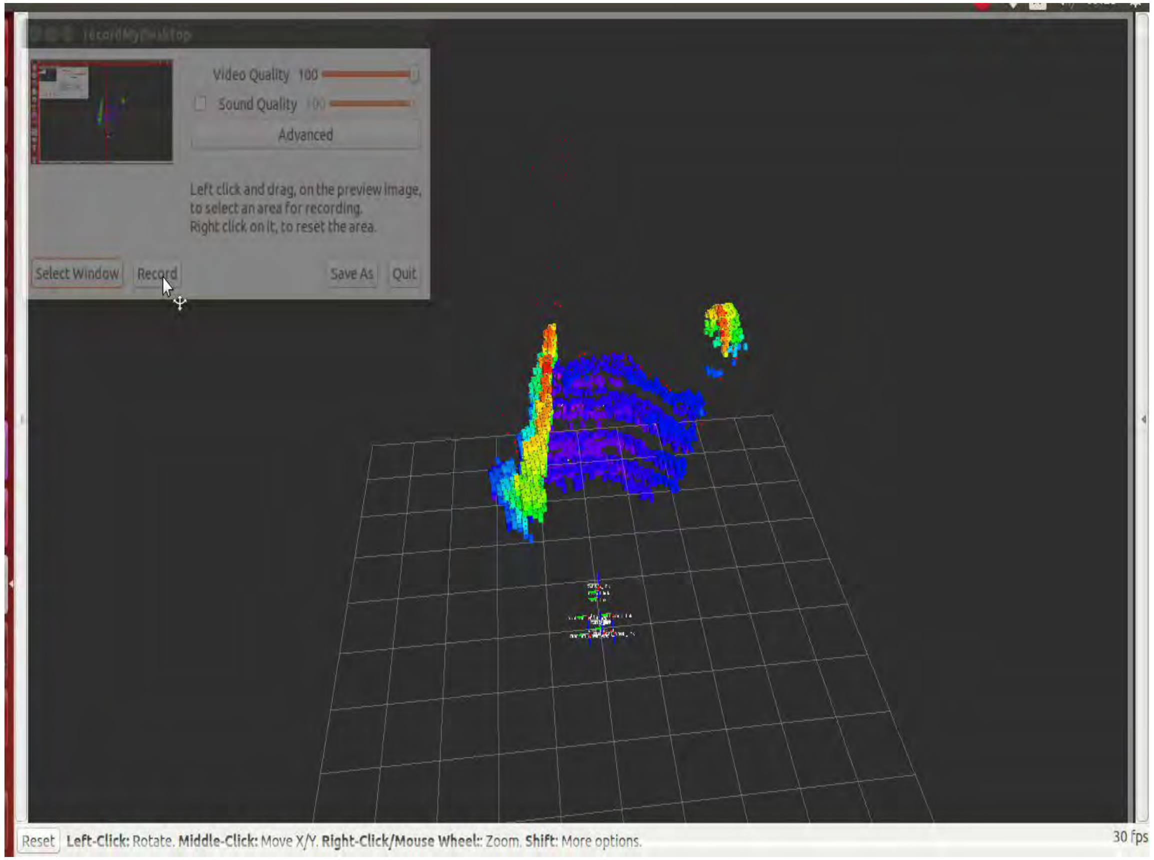
Detection object/people between 1 and 2 meters from static vehicle

Fusion
Red (R=max)
Green (G= max)
Blue (B= max)



3D CARTOGRAPHY WITH TOF CAMERA

Application: agricultural tasks in differed time using cartography environment maps (traversability maps, obstacle geometry)



TOF camera

- X,Y,Z
- Intensity value

CONCLUSIONS

-A fusion method with complementary sensors (TOF camera, Color camera LiDAR and IMU device) was developed and tested with a light mobile robot moving in vineyard, and other crops, for crop row tracking operations and for traversability operations for avoiding solid objects (lateral deviation in trajectory) or crossing grass zones, in front of vehicle, at reduced speed.

-Both sensors TOF camera and Lidar device permitted to detect natural objects, at various heights from ground and distance from vehicle.

-Despite the low resolution of TOF camera (64 x 16) different objects at various heights from ground and various sizes, such as grass and tree branches, were detected, with accuracy, with this sensor, in various lighting conditions. For obstacle detection, TOF sensor (image 64x16) gave better results than LiDAR (one plane)

-This fusion method which gives geometric and colorimetric information can be applied, in various fields, in different agricultural tasks.

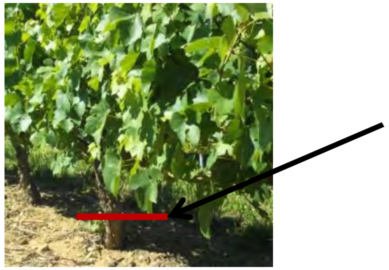
irstea

FUTURE WORKS

-Realize in the same time both operations, crop row tracking and traversability operations, with the fourth sensor, working with many perturbations (mud, bumps, a lot of grass) using a light robot or a bigger vehicle, with speeds between 1 and 3 $m.s^{-1}$

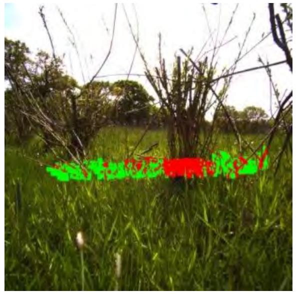
- Fusion LiDAR/Color camera for tracking operation

important point: it is necessary to find the right height of LiDAR sensor from ground, to detect crops and not grass or leaf near crops.



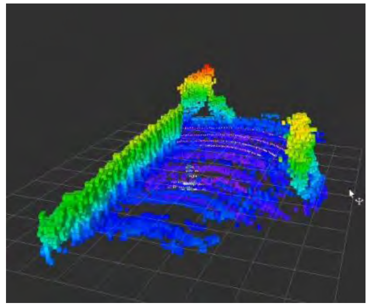
- Fusion TOF/Color camera for obstacle detection in front of vehicle

-Use new TOF camera with a higher resolution for better accuracy


Thank you for your attention

Discussion - Questions ?



Bernard BENET – Roland LENAIN
IRSTEA – Clermont-Ferrand – France
ROMEA (RObotic and Mobility for Environment and Agriculture)



Saturday, February 25th, *1st AXEMA-EurAgEng Conference*, Paris, France

AUTONOMOUS CROP ROW TRACKING OPERATION
SIMA 2017