TRACKBOD, an accurate, robust and low cost system for mobile robot person following

Jean Laneurit[1], Roland Chapuis[2], Christophe Debain[1]
[1]*National Research Institute of Science and Technology for Environment and Agriculture, 9 avenue Blaise Pascal, CS20085, 63178 Aubière Cedex, France*
[2]*Institut Pascal, 4 avenue Blaise Pascal, CS60026, 63178 Aubière Cedex, France*
jean.laneurit@irstea.fr

Keywords: ***uwb, follower robot, follow me, Kalman filter***

Abstract: Trackbod has been developed in the Baudet-Rob project whose objective is to provide a system enabling a vehicle to automatically follow a pedestrian carrying his payloads. Lots of solutions based on different sensors as ultrasonic sensors or range finder are used on flat ground but they are limited in off road situation like agricultural applications. In this article we propose a new technology based on UWB receivers coupled to a data fusion algorithm. With this technology we are able to measure in real time the distance and angle between the person to follow and the vehicle. The results show good accuracy and robustness of the following whatever the conditions of use. .

1 INTRODUCTION

Over last decade agricultural robots able to perform a wide range of agricultural chores appeared. Automatic robots are now used to weed control (Michael, 2015) (Scholz, 2015), mowing (Yang, 2013)(Husqvarna), pruning (Botterill, 2016) (Ishigure, 2013), seeding, spraying (Oberti, 2014) (Bontsema, 2014) thinning… and cobot systems are used to help farmers to milk the cows, to carry crops during harvesting, to sorting and packing them… This help to optimize production, increase competitiveness but can also prevent a lot of diseases contracted by farmers like farmer's lung, Silo-Filler's diseases, and musculoskeletal disorder

This paper talks about a cobotic system able for example to carry crops during harvesting and more precisely how to guide a robot to follow a farmer when he picks up vegetables, fruits… In the literature these systems are often called "Follow Me" systems. Their goal is to identify, to locate the human operator (the leader) and to follow him.

Some studies used lidar sensors to detect human body (Bohlmann, 2013) (Misu, 2014) or some parts of it like legs (Bellotto 2009) (Sales 2010) and arms (Cai 2014). Usually human body (or parts) is described by clusters of points. This is a rough description but can be an effective way to locate its position.

If a real recognition of the leader (the person to follow) is needed, vision systems are often used (Sakate 2009) (Bellotto 2009) to identify the human operator using classification algorithms like SVM or AdaBoost. However it's difficult to locate the human operator with vision systems because no depth information is provided here. To deal with this problem, Follow Me systems often combine lidar and vision systems to both locate and recognize human operator. For indoor context a cheap solution is to substitute both lidar and camera by RGB-D camera like Kinect (Susperregi 2013) (Mundher 2014).

In outdoor environments many problems appear: both camera and lidar sensors are very sensitive to illumination conditions (glare, setting sun, night…) and weather conditions (dust, rain, sleet, snow, fog…). In these situations both detection and recognition tasks are prone to failures. Some authors (Ćirić 2014) (Susperregi 2013) suggest to use thermal sensors to improve human operator detection in case of bad illuminations or weather conditions. Thermal information can also help to

distinguish the human operator from environmental objects like trees, wild weeds...
By combining lidar and thermal sensors with camera or RGB-D, robust Follow Me systems are effective but very expensive. To overcome this problem some authors (Sales 2010) (Ohya 2002) propose to use Radio Frequency technology instead of the previous sensors. Basically three RF modules (tags) are used. One worn by the human operator and the two others embedded on the robot. The leader is located by 2d trilateration principle based on measurement of distances between leader tag and robot tags. This kind of system is not disturbed by illumination conditions and is less sensitive of weather conditions but sensitive to propagation signal problems like propagation multipath phenomenon. These problems can be mitigated in using Ultra Wide Band technology but distance measurement between tags cannot be done simultaneously because usually communications are done on a single channel. The Trackbod system, developed in the Baudet-Rob project, provides a solution to deal with "asynchronous" trilateration by combining distance measurements with proprioceptive data coming from the robot in order to obtain a robust and accurate localization of the human operator.

Following the introduction, the second part deals with the mathematic elements of the Trackbod system. In this part we introduce how we use UWB modules to localize the leader in the robot frame and the control law allowing the robot to follow the trajectory of the leader. The third part presents results of the system when a robot follows a pedestrian on an uneven ground. Finally, the conclusion will propose new developments in order to improve the system accuracy.

2 TRACKBOD SYSTEM

2.1 Leader localization

The aim of Trackbod is to locate the robot relatively to the followed person. To do that, three UWB tags are used: one on the person to follow (the leader) and the other two on the robot. This kind of problem is usually solved by a 2d trilateration using the measurements of the two distances between the robot tags and the leader tag. However the communication between our tags can be done only on a single channel. Consequently, measures of distance between the tags cannot be done simultaneously. Several milliseconds of latencies can be seen between each measure. This problem involves unacceptable errors on the relative position estimation because distance measurements have no spatial coherence. The Trackbod system proposes to use odometry of the vehicle and an extended Kalman filter to improve spatial data consistency and to obtain an optimal localization of the leader.

2.1.1 Kalman state vector

The goal of the Kalman filter is to estimate the leader $\boldsymbol{l}$ location with respect of the body reference frame $\boldsymbol{b}$ of the follower vehicle. So the state vector $\boldsymbol{X}$ of the state system is the 2D Cartesian position of the leader:

$$X = (x_l^b, y_l^b)^T \quad \textbf{(1)}$$

Location uncertainties are also computed by the Kalman filter and are represented by a 2x2 covariance matrix $\boldsymbol{P}$.

2.1.2 Kalman prediction step

In this article we assume that the leader is followed by a steering vehicle (see figure 1). Odometry data is used to compute the displacement of this vehicle between two distance measurements and to provide a good estimation of a priori position of the leader. Basically an Ackermann kinematic model is considered for this kind of vehicle:

$$\begin{cases} \dot{x}_r^w = v_r \cos\theta \\ \dot{y}_r^w = v_r \sin\theta \\ \dot{\theta}_r^w = v_r \dfrac{\tan\delta_r}{L} \end{cases} \quad \textbf{(2)}$$

Where:

- $(x_f^w, y_f^w, \theta_f^w)^T$ is the pose the follower robot in the world reference frame $\boldsymbol{w}$
- $\boldsymbol{v_r}$, $\boldsymbol{\delta_r}$ and $\boldsymbol{L}$ are respectively the linear speed, the steering angle and the wheel base of the robot

In discrete time, the robot displacement in the world reference frame between two distance measurements is given by:

$$\begin{cases} x^w_{l,k+1} = x^w_{l,k} - \Delta_D \sin\left(\theta^w_{l,k} + \Delta_\theta / 2\right) \\ y^w_{l,k+1} = y^w_{l,k} - \Delta_D \cos\left(\theta^w_{l,k} + \Delta_\theta / 2\right) \\ \theta^w_{l,k+1} = \theta^w_{l,k} + \Delta_\theta \end{cases} \quad \textbf{(3)}$$

Where:

- $\Delta_\theta = v_{l,k} \dfrac{\Delta_T \tan \delta_{r,k}}{L}$
- $\Delta_D = v_{l,k} \Delta_T$

With Δ_T the elapsed time between step $\boldsymbol{k}$ and $\boldsymbol{k+1}$, namely the sampling period**.** These equations describe the movement of the vehicle in the world. However, our problem is to determine the movement of the leader in the reference frame of the vehicle. In assuming that the leader does not move between two distance measurements, a priori position of the leader can be computed like that:

$$\begin{pmatrix} x^b_{l,k+1} \\ y^b_{l,k+1} \end{pmatrix} = R(\Delta_\theta)^T \begin{pmatrix} x^b_{l,k} - \left(x^w_{f,k+1} - x^w_{f,k}\right) \\ y^b_{l,k} - \left(y^w_{f,k+1} - y^w_{f,k}\right) \end{pmatrix} \quad \textbf{(4)}$$

Using equation (3) into equation (4), a priori position can be simply deduced from odometry information:

$$\begin{pmatrix} x^b_{l,k+1} \\ y^b_{l,k+1} \end{pmatrix} = R(\Delta_\theta)^T \begin{pmatrix} x^b_{l,k} + \Delta_D \sin(\Delta_\theta / 2) \\ y^b_{l,k} - \Delta_D \cos(\Delta_\theta / 2) \end{pmatrix} \quad \textbf{(5)}$$

Where $R(\Delta_\theta)$ is the rotation matrix by an angle Δ_θ around z-axis. Of course, the leader may move at the same moment. But his displacement is unknown. As human displacements are non-holonomic they are usually described by a kinematic stop model:

$$\begin{cases} \dot{x}^w_l = \dot{x}^b_l = 0 \\ \dot{y}^w_l = \dot{y}^b_l = 0 \end{cases} \quad \textbf{(6)}$$

This kind of model is available in both world and follower reference frames. Taking into account this constraint, equation (5) can be rewritten as:

$$\begin{pmatrix} x^r_{p,k+1} \\ y^r_{p,k+1} \end{pmatrix} = R(\Delta_\theta)^T \begin{pmatrix} x^r_{p,k} + \Delta_D \sin(\Delta_\theta / 2) \\ y^r_{p,k} - \Delta_D \cos(\Delta_\theta / 2) \end{pmatrix} + \mathrm{N}(0, Q_{xy}) \quad \textbf{(7)}$$

Where $\mathrm{N}(0, Q_{xy})$ is a 2D normal distribution zero mean and a covariance matrix Q_{xy} defined by:

$$Q_{xy} = I\left(\sigma^r_{xy} \cdot \Delta_T\right)^2 \quad \textbf{(8)}$$

σ^r_{xy} represents the standard deviation of the movement that could be performed by the leader during one second in both x and y directions, and Δ_T the elapsed time between times k and $k+1$.

Equation of prediction of the Kalman filter can be easily deduced from equation (7). Then, a priori state vector $X_{k/k-1}$ at time $\boldsymbol{k}$ is given by:

$$X_{k/k-1} = R(\Delta_\theta)^T \left(X_{k-1/k-1} - \begin{pmatrix} -\Delta_D \sin(\Delta_\theta / 2) \\ \Delta_D \cos(\Delta_\theta / 2) \end{pmatrix} \right) \quad \textbf{(9)}$$

and its associated covariance matrix by:

$$P_{k/k-1} = R(\Delta_\theta)^T \left(P_{k-1/k-1} + G_k Q_u G_k^T\right) R(\Delta_\theta) + Q_{xy} \quad \textbf{(10)}$$

With Q_u is the covariance matrix describing the uncertainties of proprioceptive data:

$$Q_u = \begin{pmatrix} \sigma^2_{v_r} & 0 \\ 0 & \sigma^2_{\delta_r} \end{pmatrix} \quad \textbf{(11)}$$

Where σ_{v_r} and σ_{δ_r} are respectively the standard deviation on linear speed and the steering of the robot.

2.1.2 Kalman udapte step

Using equations (9) and (10) a rough estimation of the position of the leader is computed at each time. In order to improve this estimation, trilateration concept is kept but using a single distance measurement at each step as they cannot be done simultaneously. Then at time k a distance observation between the follower tag n and the leader tag can be established. Assuming that the leader tag and leader locations are the same we obtain:

$$d_{n,k} = \sqrt{\left(x^b_{l,k/k-1} - x^b_{t,n}\right)^2 + \left(y^b_{l,k/k-1} - y^b_{t,n}\right)^2} \quad \textbf{(12)}$$

Where $\boldsymbol{d_{n,k}}$ is the distance between the leader and the tag $\boldsymbol{n}$ located on the robot at position $(\boldsymbol{x^b_{t,n}}, \boldsymbol{y^b_{t,n}})^{\boldsymbol{T}}$. Update equations of the Kalman filter can be easily deduced from equation (12):

$$\begin{aligned} K_{n,k} &= P_{k/k-1}H^T_{n,k}\left(H_{n,k}P_{k/k-1}H^T_{n,k} + \sigma^2_d\right)^{-1} \\ X_{k/k} &= X_{k/k} + K_{n,k}\left(d_{n,k} - d_{n,k/k-1}\right) \\ P_{k/k} &= \left(I - K_{n,k}H_{n,k}\right)P_{k/k-1} \end{aligned} \quad \textbf{(13)}$$

Knowing that Jacobian matrix $H_{n,k}$ is:

$$H_{n,k} = \left(\frac{x_{k/k-1}}{d_{n,k/k-1}} \; \frac{y_{k/k-1}}{d_{n,k/k-1}} \right) \quad \textbf{(14)}$$

In order to achieve the “trilateration”, two tags are embedded on the robot. Distance between the first tag and the leader is measured at time $\boldsymbol{k}$ and distance between the second tag and the leader is measured at time $\boldsymbol{k+1}$ and so on. In this way spatial coherency of distance measurement is ensure and a precise localization of the leader can be obtained.

2.2 Robot control

Once the leader position is known, it is possible to control the vehicle in order to follow him. This position can be considered in polar coordinates i.e the distance $\boldsymbol{\rho}$ between the leader and the vehicle and the direction $\boldsymbol{\theta}$ where the leader is located. The goal is to drive toward the leader ($\boldsymbol{\theta \to 0}$) and to keep a distance $\boldsymbol{\rho_c}$ between the vehicle and the leader. A common pursuit control is used to achieve this purpose. Then at each time $\boldsymbol{k}$, a proportional controller is used to compute the wheel steering angle $\boldsymbol{\delta_f}$:

$$\delta_{f,k} = Kp_\theta\left(\theta_k - \theta_c\right) \quad \textbf{(15)}$$

Where $\boldsymbol{Kp_\theta}$ is the proportional gain. Here the goal is to turn the steering wheels toward the leader to follow him. A proportional integral controller is used to compute the linear speed $\boldsymbol{v_f}$ of the follower vehicle:

$$v_{f,k} = Kp_\rho\left(\rho_k - \rho_c\right) + Ki_\rho \sum_{i=0}^{k}\left(\rho_k - \rho_{c,k}\right) \quad \textbf{(16)}$$

Where $\boldsymbol{Kp_\rho}$ and $\boldsymbol{Ki_\rho}$ are respectively the proportional gain and integral gain. When the leader moves toward the vehicle $\left(\rho_k - \rho_c\right)$ becomes negative, the linear speed too and the vehicle backs up. This kind of motion will be forbidden for safety purpose and to allow the leader to approach the vehicle in order to pick up or put objects on the vehicle.

3 RESULTS

In order to demonstrate the capabilities of Trackbod we have tested it in the 3D environment of the park of Irstea. A GPS RTK receiver with a single antenna has been carried by the leader and another one with two antennas has been embedded on the vehicle (see figure 1). Then at each instant it is possible to known the ground truth of the position of the leader and the position and orientation of the follower robot in the world reference frame.

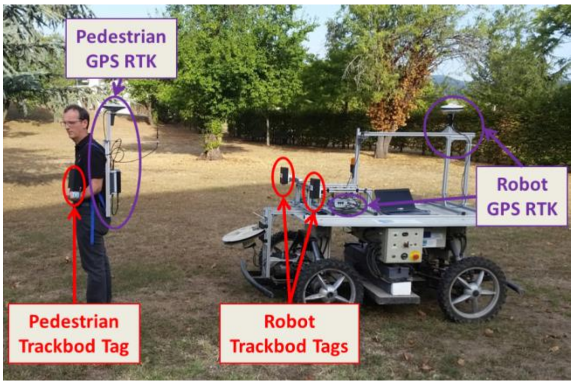

Figure 1: image of the leader and the follower robot both equipped with GPS RTK in order to get the ground truth and to evaluate the precision of the Trackbod system.

With this equipment it is possible to measure the error between the pedestrian path and that of the robot. In this test the following task has been performed along a path about 250 meters in length and the following distance between the leader and the robot has been set to 4 meters. The trajectory includes straight lines and left curves. The figure 2 shows the trajectories of both leader and follower robot in the world reference frame (GPS). We can see that the robot follows correctly the leader during straight line but cuts curves. This is due to holonomic constraints of the vehicle.

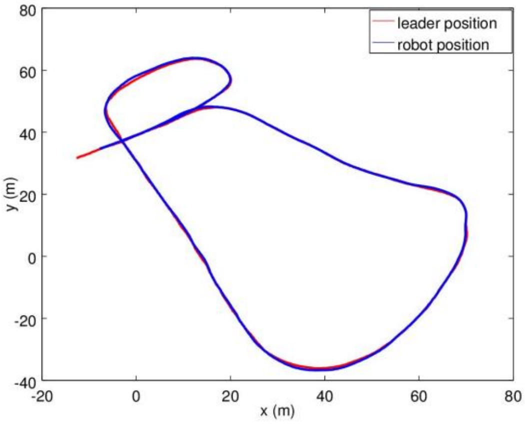

Figure 2: Trajectories of both leader and follower robot in the world reference frame.

To evaluate the accuracy of the Trackbod system, we have computed errors between the trajectory of leader and the robot trajectory.

These results can be seen in details in Figure 3 where the lateral and the longitudinal position of the leader in the reference frame of the vehicle are presented. When the leader walks in a straight line (green areas) the lateral error of position tends toward zero. Instead during curves the lateral error position increases because of our current control which take into account only the head and the distance of the leader and not its lateral position (see eq 15).

So for straight line trajectories, we can observe a good accuracy of the Trackbod system (longitudinal offset is closed to the input value of 4 meters and lateral offset is closed to zero). For curve part of the trajectory, the lateral error can reach one meter and the longitudinal error can reach two meters.

Some variations in longitudinal position can be seen when the leader walks on straight lines (for instance at the end of the second green area). They are due to the swing of the antenna of GPS receivers because both leader and follower robot move on an uneven terrain (see Figure 4). But in reality the following is smooth. (https://youtu.be/C6dpAP_l3u4))

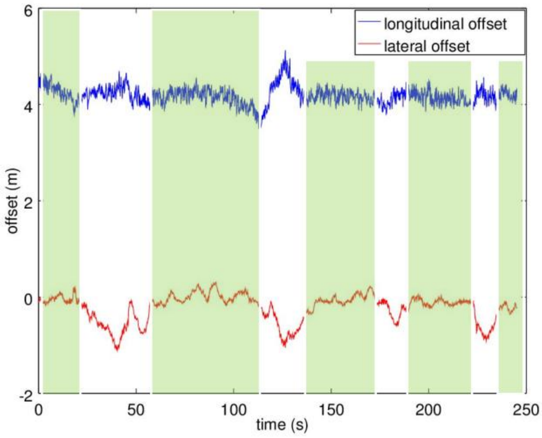

Figure 3: Lateral and longitudinal position of the leader in the reference frame of the vehicle trajectory. Green areas show when the leader follows a straight line.

Figure 4: Trackbod is used with a robot moving on uneven terrain with steep slopes.

4 CONCLUSIONS

The problematic of follower robot is relevant for different domains (industry, agriculture, logistic, military…). One of the main difficulties of such an application is to ensure the robustness of the tracking system especially in agriculture. In the Baudet-Rob project we tested various sensors as Lidar or vision system but none were robust enough to be used on agricultural land. So we developed the Trackbod System in order to equip agricultural machinery. Trackbod is very robust to the conditions of use such as dust environment, rain or frog…
Accuracy of the system depends of the accuracy of the measurements given by the tags and the control

law capabilities. If we consider our control law given by the equation (15) we can see that it includes only a correction for the heading error of the vehicle. This is relevant in a straight line but this leads to errors in the curves because the robot has a tendency to cut the path. So future work will deal with more performant control laws such as it is proposed in (Lenain, 2016).

ACKNOWLEDGEMENTS

This work has been sponsored by the French National Research Agency through the project “ASMA-2015-Baudet-Rob2” and the through the MATGRID program of the Auvergne region.

REFERENCES

Ohya A., Nagumo Y., Gibo Y, 2002. Intelligent escort robot moving together with human-methods for human position recognition, Joint 1st International Conference on Soft Computing and Intelligent Systems and 3rd International Symposium on Advanced Intelligent Systems.

Bohlmann K., Beck-Greinwald A., Buck S., Marks H. and Zell A, 2013 Autonomous Person Following with 3D LIDAR in Outdoor Environments. Journal of Automation Mobile Robotics and Intelligent Systems.

Bellotto N., Hu H., 2009. Multisensor-based human detection and tracking for mobile service robots, IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics.

Bontsema, J., Hemming, J., Pekkeriet, E.J. 2014. CROPS : high tech agricultural robots, AgEgn’14, International Conference of Agricultural Engineering, Zurich, Austria.

Botterill T., Paulin S., Green R., Williams S., Lin J., Saxton W., Mills S., Chen X., Corbett-Davies S., 2016. A robot system for pruning grape vine, Journal of Field Robotics.

Cai J. and Matsumaru T, 2014. Human Detecting and Following Mobile Robot Using a Laser Range Sensor, Journal of Robotics and Mechatronics.

Ćirić Ivan T., Ćojbašić Žarko M., Nikolić Vlastimir D., Igić Tomislav S., Turšnek Branko A.J., 2014 Intelligent optimal control of thermal vision-based Person Following Robot Platform. Journal of Thermal Science

Ishigure Y., Hirai K., Kawasaki H., 2013. A Pruning Robot With a Power-Saving Chainsaw Drive, ICMA’13 International Conference on Mechatronics and Automation. Takamatsu, Kagawa, Japan.

Michaels, A., Haug S, 2015. Vision-Based High-Speed Manipulation for Robotic Ultra-Precise Weed Control. IROS’15 International Conference on Intelligent Robots and Systems. Hamburg. Germany.

Misu K., Miura J., 2013. Specific Person Detection and Tracking by a Mobile Robot using 3D LIDAR and ESPAR Antenna, IAS’14 International Conference on Intelligent Autonomous Systems. Padova. Italy.

Mundher, Z., Zhong J.,2014 A Real-Time Fall Detection System in Elderly Care Using Mobile Robot and Kinect Sensor. International Journal of Materials, Mechanics and Manufacturing.

Oberti R., Marchi M., Tirelli P., Calcante A., Iriti M., Hocevar M., Baur J., Schütz C., Pfaff J.; Ulbrich H., 2014. The CROPS agricultural robot: application to selective spraying of grapevine’s diseases. AgEgn’14, International Conference of Agricultural Engineering, Zurich, Austria.

Sales J., Marín R., Cervera E., Rodríguez S., Pérez J., 2010. Multi-Sensor Person Following in Low-Visibility Scenarios. *Sensors*.

Scholz, C., Kinski, D., Kohlbrecher, M., Mentrup, D., Ruckelshausen, A, 2015. Camera-based selective weed control application module (“Precision Spraying App”) for the autonomous field robot platform BoniRob. AgEgn’14, International Conference of Agricultural Engineering, Zurich, Austria.

Satake J., Miura J., 2009.Robust stereo-based person detection and tracking for a person following robot, ICRA’09 International Conference on Robotics and Automation, Kobe, Japan.

Susperregi L., MartÃnez-Otzeta J.M., Ansuategui, A. and Ibarguren A., Sierra B., 2013. RGB-D, laser and thermal sensor fusion for people following in a mobile robot. International Journal of Advanced Robotic Systems.

Yang J. and Chung S., 2013. Vision-based localization and mapping for an autonomous mower. IEEE Intelligent Robots and Systems (IROS). Tokyo, Japan.

Lenain, R., Morin, P., Samson, C. - Sicillano, B., Khatib, O. - 2016. Motion control of wheeled mobile robots. *Handbooks of robotics, Springer, 2ème ed., 47 p.*