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Development of a Teleoperational Robot For Feasibility Study of Using it in Agricultural Tasks

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Abstract

To assess teleoperational controlled off-road vehicle possibility in an actual scale, and to experimentally evaluate the accuracy, the SAPHT, a renewable energy based tractor, was equipped with some autonomous guidance systems. Beside, controlling the developed system in a teleoperational mode, the system can also be used for conventional in-cab operation. Tests based on the ASABE standard document (X587), were carried out and data were collected using an ultrasonic sensor and an image processing method, mainly Hough transform algorithm. Using MATLAB software, different cases were compared to one another by RMSE, STD, maximum deviation error and mean error parameters. Experimental results shows the RMSE of teleoperational mode is several times in comparison to that of manually performed tests. In teleoperational mode, RMSEs of trajectories with respect to three reference points (diverse distance and height) were obtained to be about 19, 21 and 26 cm. Although, the system is applicable for many operations such as mowing, fertilization, spraying and secondary tillage, however, the technique is recommended with caution for precision operations.

Keywords: Teleoperation; Autonomous; Hough transform; Remote guidance; Mobile robot.

1. Introduction

Considering the necessities of food supply for the predicted increased world population in the following centuries, imply to increase the efficiency, using more accurate and automated systems in the future farms. Field robotics and vehicle automation represent a second leap in agricultural technology. Although automated guided vehicles are invented approximately one century ago(WILLRODT, 1924), increasing computational powers, availability of cheap sensors and decreasing farm labors especially in the developed countries, have led to rapid development of this technology in the last decade. These intelligent robots aim to improving efficiency (productivity, energy and time), increasing work-hour, accuracy enhancement, saving labor and protecting the operator from hazardous environment (ergonomic viewpoint).

Although much development in agricultural automation was achieved in recent years, much work is required to acquire farmer's consensus about autonomous vehicles. Some issues such as safety, economy, implement standardization and technical service support in the entire world are merit to consideration(Mousazadeh, 2013). Some main functions that an intelligent vehicle can perform automatically are: navigation, implement control, mapping and data gathering. Among them, navigation is the most important, sensitive and sophisticated one. Navigation ranges from a guidance assistance device, teleoperation or remote guidance, semi-autonomy (autopilot), to full-autonomy(Rovira Más, Zhang, & Hansen, 2010). In teleoperation, the vehicle is still controlled by the operator (either to guide the vehicle or to actuate any of its attachments), but from outside the cabin, so little intelligence is required. Cui et al. (2003) defined the teleoperation as a means to operate a robot using human intelligence(Cui, Tosunoglu, Roberts, Moore, & Repperger, 2003). In teleoperation two scenarios are applicable. In the first scenario, the operator presents in the field but at a distance from vehicle(Fong & Thorpe, 2001) which can protect the operator from vibration, noise, and other hazards. In the next scenario, the operator controls one or several vehicles simultaneously from PC based GUI (Graphical User Interface) environment from office. However, in teleoperation mode, the absence of an operator on the vehicle would be a great anxiety from safety viewpoint. Wireless communications for remote control of large machines have not reached the desired level of reliability yet, and more research is required in this context.

Despite advances in autonomous vehicles, there will always be a need for human involvement in vehicle teleoperation especially in tasks such as exploration, reconnaissance and surveillance. Jarvis (2011) reviewed remote teleoperation of robotic vehicles, in outdoor rough terrain situations, with sensory feedback and path guidance support in which the navigation system used a forced feedback for assisted teleoperation. He concluded that the described localization methodology has been successful in demonstrating the speed, accuracy and reliability of the approach (Jarvis, 2011). Murakami et al. (2008) developed a teleoperation system for a hydro-static transmission drive crawler-type manure spreader. The system used a set of wireless internet protocol communication devices for the remote operator. Experimental tests showed that the vehicle could travel straight with a maximum lateral error of 0.3 m in supervisory mode (Murakami et al., 2008). Antonio et al. (2007) converted a remote-controlled boat to an autonomous surface vehicle capable of operating by teleoperation (game-controller joystick) or through an autonomous program (de Menezes Pereira, 2007). Borenstein et al. (1990) developed a tele-autonomous guidance for mobile robots and tested successfully. Under tele-autonomous control, the environment conditions and the instantaneous direction of the vehicle dictated whether the operator or the vehicle takes the leading role in directing the vehicle to the target and to what degree (Borenstein, 1994). Gomez et al. (2011) developed an electromyographic (EMG)-based human-machine interface system for steering a tractor. This system was regarded as a novel generation of teleoperation systems. This device, by means of 14 saline sensors, measured and processes EMG and electroencephalographic (EEG) signals from the scalp of the driver. It is concluded that it is possible to steer a tractor by an EMG-based human-machine-interface with almost the same accuracy as with manual steering(Gomez-Gil, San-Jose-Gonzalez, Nicolas-Alonso, & Alonso-Garcia, 2011). Longo et al. (2010) built a multipurpose outdoor vehicle, to be used in different applications. The control electronics was designed to provide teleoperated,semi-autonomous and fully autonomous modalities. The simplest one was the teleoperated modality in which a remote user by using a joystick could send direct commands to the robot in order to move forward, backward or turn left or right at different speeds(Longo, Pennisi, Bonsignore, Muscato, & Schillaci, 2010).

Hough transform was used in many researches for row and line detection, which is used in this research too. Bakker et al. (2008) developed a new approach for row recognition which was based on grey-scale Hough transform on intelligently merged images. They concluded that the algorithm is able to find the row with mean errors of 5 and 11mm with standard deviations of 6 and 11mm(Bakker et al., 2008). Keicher et al. (2000) reasoned that the Hough transform can be used to find the guidelines, by assuming a row of plants as a line and weeds as noise(Keicher & Seufert, 2000).

The main objective of this research is to develop a teleoperation based control system for guidance and controlling of an actual scaled agricultural off-road vehicle with special platform and assessment the impact of operator position on controlling accuracy. This renewable energy based electric vehicle fitted with standard three-point-hitch (3PH) and power-take-off (PTO) system and was controlled remotely by transceiver. Evaluating the accuracy and precision of the developed system in the actual circumstances and comparison to that in the-cab mode is the next promise of the research.

2. Materials and methods

Teleoperation is a promising compromise between manual control and fully autonomous operation, in which the operator can feel immersed, as if at the site, while still being located at a distance. For the robotized tractors, some scientists believe that conventional tractors platform would be beneficial, whereas others are preferences by new small platforms. However these agricultural tractors demand special requirements like: CVT (Continuous Variable Transmission), automatic steering and braking systems, and unmanned actuator for PTO and 3PH. Considering all, the SAPHT (Solar Assist Plug-in Hybrid electric Tractor) was used through this project for development and evaluation of a teleoperation control system. The SAPHT is a light - duty tractor. All detailed designs and prototyping of the SAPHT were implemented in the laboratories of the Department of Agricultural Machinery Engineering, University of Tehran. Two different sources supply the SAPHT with electric energy: onboard PV arrays, and electricity from the grid. SAPHT tractor uses two 10.5 kW DC (approximately 28 hp in total) series motors on rear axles for propelling. Another 16.5 kW DC motor is used to operate the 3PH and PTO system. It uses the standard PTO in 540 and 1000 rpm(Mousazadeh et al., 2011).

Although the SAPHT propulsion system was CVT, the forward/backward direction control was based on a power switch that had to be actuated manually as well as steering system. To be operated as teleoperation, the direction control switch is replaced by two power DC contactors and the steering system was fully converted to electrical. The developed system not only aims to teleoperation but can also be used for conventional in-cab operation by toggling a switch. Succeeding that two transceivers were utilized for communicating between operator and vehicle.

2.1- Steering system

The steering mechanism is shown in **Figure 1**. As schematically shown, one approximately 800 W PM-DC motor with a gearbox, is used to actuate the steering shaft. To maintain the desired heading, a power electric board with an electronic control unit was designed and constructed based on full H-bridge. The constructed electric board uses four MOSFETs (metal oxide semiconductor field-effect transistor) and actuated by means of a microcontroller that controls the direction of rotation and provides a soft start as well.A rotational potentiometer was installed on the steering wheel and the output of this sensor was fed back into the control loop. The sensor was calibrated to establish a relationship between its output and the wheel angle (in degrees). According to the received command, the steering system can be updated approximately by maximum 20 Hz. However, in teleoperation steering, allowed typical delays in the digital transmission would be less than 100 ms(Suomela, 2001). To achieve a satisfactory and simple steering performance, a P controller was calibrated and used.

2.2. Transceiver structure

Two transceivers were used for communication between operator and the vehicle. One of them was located in a portable box for sending operator commands and the other one was located on the vehicle ECU box to receive the transmitted data, and to act as a master for some slave systems as well (Figure 2). The controlling commands sent by the user were: steering control, forward/backward selection, velocity, PTO activation (540 or 1000 rpm) and 3PH engagement. An LCD on the transmitter illustrates states of the parameters. According to the received coded commands, the master triggers the desired slave and loads the structures on it. As all the sent data were updated by minimum 120 Hz between transceivers and communication speed inside the control system and master and slaves was more than 120 Hz so the steering system update frequency was restricting part of control system which limits the total refresh frequency to about 20 Hz (50 ms). Therefore the total delay between operator and vehicle is very low and there is no need to delay compensation methods.

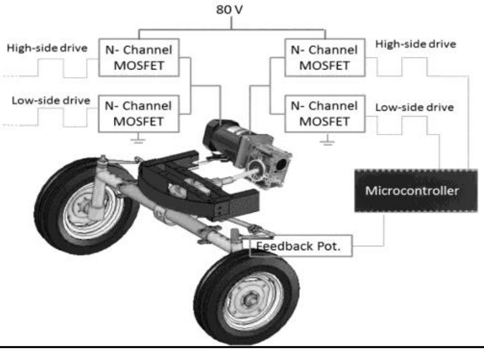


Figure 1. Architecture of electric and mechanical system for SAPHT steering.

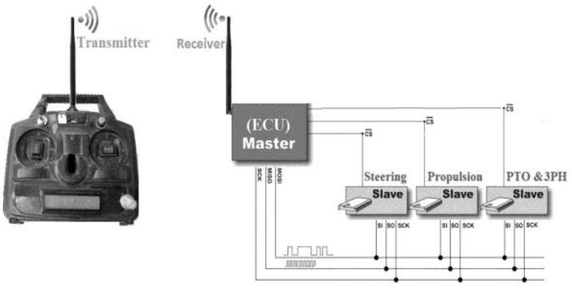


Figure 2. Communication between transmitter (left) and receiver (right).

2.3. Evaluation planning

Due to the novelty of these systems, there are no generally applied dynamic test standards for these approaches. However, the American Society of Agricultural and Biological Engineers (ASABE) have recently provided two standards: GPS dynamic test standard (X587) and auto-guidance test standard (X605). The standard X587(ASABE, 2007) was used in this research with some changes due to existing limitations. Considering dimension of the test campus, two straight lines each by 40 m in length that were linked by a turn of 5 m were sketched using white color (**Figure 3**). To evaluate accuracy of designed teleoperation system the SAPHT was driven on the sketched lines as guess rows and the offset drift was measured and compared with manual driving results. In the manual mode, the travel speed was set to 2, 4 and 6 km/h, with four replications. In teleoperation mode, the accuracy was not acceptable for speeds above 2 km/h (e.g. in 4 km/h the vehicle fluctuated by maximum error of one meter approximately). Therefore, the travelling speed was limited to 2 km/h, but in three different positions as shown in **figure 3**: 1) two meter far from the corner of the field by approximately two meter in height, 2) from center of the field, and 3) 10 meter far from the center of the field by approximately five meter in height. The SAPHT speed was accurately read by an encoder on the drive wheel. Drivers distance from field and vehicle has a serious effect on control quality. Therefore the driver's position (distance and height from the field) is an important factor in controlling test.

Figure 3. Test track for evaluation of the SAPHT at three positions.

Two scenarios were assessed for data acquisition. In first scenario an ultrasonic was used to measure the distance from a reference. To perform this test a pedestrian was carried a big flat wooden page with a fix distance from sketched lines parallel to SAPHT. Due to weakness of ultrasonic sensors in headlands the second mthode was used. The second method used image processing advantages to calculate deviation from target. A digital CCD color camera was installed on the SAPHT to capture and save images of the path. Then, the line was detected in the image and drift from the front wheel was calculated in increments of 3.5, 7 and 10 cm of forward movement for speeds of 2, 4 and 6 km/h, respectively. Six main stages of drift mesurment algorithm were developed in c# environment were: selecting the region of interest, thresholding and binarization of the image, defining target points, sketching the path line, calculating offset and exporting data to Excel. For line detection two basic approaches were used: regression analysis and the Hough transform. Regression is very sensitive to the presence of outliers, which are certainly not rare in digital images. A superior approach is provided by the Hough transform (Rovira Más et al., 2010). The regression was fitted using Equations 1-3 when some points with known coordinates, (x, y), are available;

$$\hat{y} = a + b.x \qquad (1)$$

$$a = \bar{y} - b\,\bar{x} \qquad (2)$$

$$b = \frac{\Sigma(x-\bar{x})(y-\bar{y})}{\Sigma(x-\bar{x})^2} \qquad (3)$$

where ŷ is the predicted value, a, is the intercept and b, is the slope of the line.

The Hough transform is based on the principle that a line can be represented by a point in a polar coordinates system(Doerr, 2010). The transformation takes place between the image space represented by the pixels (x, y) of the image and the parameter space (ρ, θ) in which linear features are detectable. The transformation is carried out by applying Equation (4) to every pixel in the image. When the transformed points lie in a straight line, all of the sinusoids in the parameter space will cross at one point defined by (ρL, θL). The inverse transformation (Equation (5)) represents the best fitted line in the image space (Rovira Más et al., 2010).

$$\rho = x \,.\, \sin\theta + y\cos\theta \qquad -90^\circ < \theta < 90^\circ \tag{4}$$

$$y = \frac{\rho_L}{\sin\theta_L} - \frac{\cos\theta_L}{\sin\theta_L}.x \tag{5}$$

After thresholding the white trajectory line, some red points are defined, and Hough transform is applied. To define the position of parameter point, (ρL, θL), the pixel that is crossed by maximum number of sinusoids was detected in application. In **Figure 4-a**, the fitted line by Hough transform is shown in blue, while the red line illustrates the fitted line by regression method, that is affected by outliers. In Hough environment as shown in **Figure 4-b**, number of sinusoidal curves is equal to the number of red points in the image environment.

However, the main advantage of Hough transform, compared to commonly used methods such as least-squared error of fitting lines to image data, is that even if group points vary to some extent, seeking for a straight line is still possible. Also, processing is collectively possible even when there are two or more straight lines in the image data. The disadvantage is that the computational complexity is large (Barawid Jr, Mizushima, Ishii, & Noguchi, 2007). However data acquisition and error measurement was performed with high accuracy due to offline image processing using Hough Transform and since regression method was unable to estimate the accurate line offset it was dismissed.

Whereas the ultrasonic sensor does not provide accurate data especially in the curved paths as headlands, all evaluations were carried out based on the camera data. In addition, the ultrasonic data was affected by accuracy of pedestrian guidance. However, the ultrasonic data was recorded for comparison

After data acquisition, some computational parameters such as RMSE, STD, maximum and average offset were calculated to compare different scenarios.

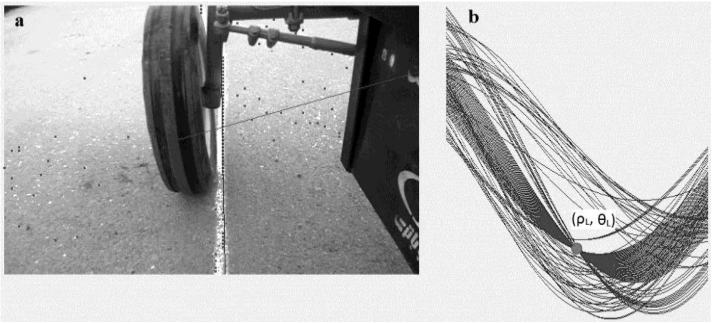
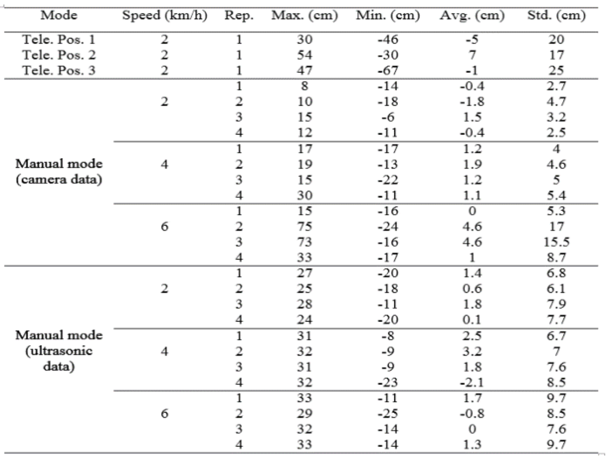


Figure 4. (a) Image space - regression and Hough lines (b)

3. Results and discussion

The evaluation tests were carried out under different circumstances. Some assessed parameters for different evaluations are illustrated in **Table (1)**. According to this table, teleoperation mode shows more offset errors in comparison to that

Table 1. Statistical parameters for different experiment



Mode	Speed (km/h)	Rep.	Max. (cm)	Min. (cm)	Avg. (cm)	Std. (cm)
Tele. Pos. 1	2	1	30	-46	-5	20
Tele. Pos. 2	2	1	54	-30	7	17
Tele. Pos. 3	2	1	47	-67	-1	25
Manual mode (camera data)	2	1	8	-14	-0.4	2.7
		2	10	-18	-1.8	4.7
		3	15	-6	1.5	3.2
		4	12	-11	-0.4	2.5
	4	1	17	-17	1.2	4
		2	19	-13	1.9	4.6
		3	15	-22	1.2	5
		4	30	-11	1.1	5.4
	6	1	15	-16	0	5.3
		2	75	-24	4.6	17
		3	73	-16	4.6	15.5
		4	33	-17	1	8.7
Manual mode (ultrasonic data)	2	1	27	-20	1.4	6.8
		2	25	-18	0.6	6.1
		3	28	-11	1.8	7.9
		4	24	-20	0.1	7.7
	4	1	31	-8	2.5	6.7
		2	32	-9	3.2	7
		3	31	-9	1.8	7.6
		4	32	-23	-2.1	8.5
	6	1	33	-11	1.7	9.7
		2	29	-25	-0.8	8.5
		3	32	-14	0	7.6
		4	33	-14	1.3	9.7

of manual. For example, Std. in teleoperation mode was more than 17, while the maximum Std. in manual mode with 2 km/h was 4.7 cm. In teleoperation, guiding from the center of the field, leads to least offset error, while by locating the operator farther from the center of the field, the error was increased. The error in all tests increases by increasing forward speed. In this table, maximum offsets from outside and inside of the desired line are shown by Max and Min, respectively.

For more assessment and comparison between different modes, all collected data were linked to MATLAB programming toolbox and obtained data were plotted as trajectories. Since the third replication has the nearest RMSE to the average, it was chosen as deputy of this mode for next comparisons.

Figure 5, illustrated test trajectories for data obtained from ultrasonic sensor and camera in manual mode, at 2 km/h. These typically sketched paths belong to third replication. The RMSEs for ultrasonic and camera, were calculated to be 8.1 and 3.5 cm, respectively. This shows the prominence of image processing method in comparison to that of ultrasonic for vehicle guidance and data acquisition. Although the ultrasonic sensor was installed on the king pin of front wheel, as illustrated in figure 5, the ultrasonic data were missed in the turning path due to the different wooden pad and sensor headings. The results of teleoperation tests from three different positions are shown by trajectories in **Figure 6**. According to this figure, controlling from center of the field (position 2) with RMSE of 18.9 cm gives the best result compared to that of position 1 and position 3. However, it is concluded that the accuracy of guidance, primarily is depending on some critical parameters such as operator experience, designed system capabilities, position of operator and type of the terrain. Although it was not possible to carry out the tests in a real agricultural field, it is expected that, guidance between plant rows could increase the accuracy. Because, distinction of plant rows is more convenient than sketched lines.

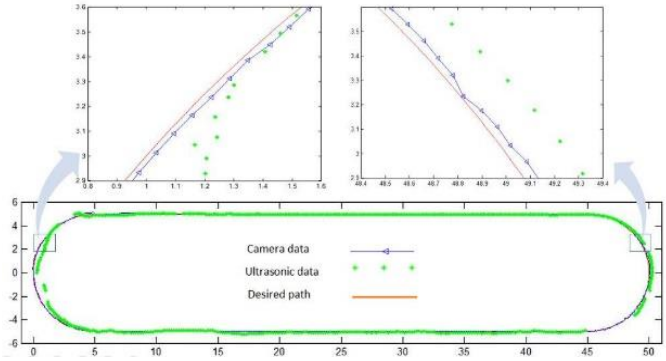


Figure 5. Comparison of trajectories obtained from ultrasonic sensor and image processing in manual mode at 2 km/h.

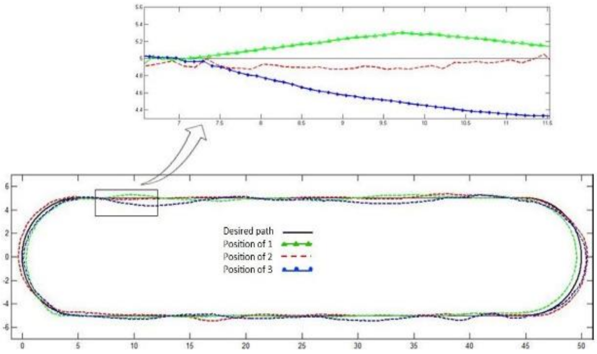


Figure 6. Comparison between different positions in teleoperation mode

Considering the teleoperation result, this control mode would be recommended with caution for precision operations. For operations that require very closely guidance, this system needs to be upgraded. However, this system is now applicable in many operations such as (not all): mowing and moving, fertilization, spraying. Comparison trajectory for the deputy of manual mode at 2 km/h and the best teleoperation mode (position of 2) is shown in **Figure 7**. This figure illustrates the excellence of manually guidance path in comparison to that of teleoperation, especially during turning. It should be noted at most operations the turning takes place at the end of the row, so accuracy in the turning would not be as important as the straight path.

The RMSEs of all experiments were compared using bar chart in **Figure 8**. In this figure, replications are shown by “Rn”, while “M.V.” and “U.S.” refer to machine vision(camera data) and ultrasonic sensor, respectively. According to this figure, the RMSE of teleoperation tests was several times of the manually performed tests. In all manual cases, camera provided more accurate data in comparison to that of ultrasonic sensor. Increasing forward speed causes an increase in the corresponding RMSE value as well.

According to **Figure 7-8**, in teleoperation mode, the best result was obtained from position 2 (center of the field) where the RMSE was found to be 18.9 cm. The maximum offset error from desired path was happened at the headlands, where the operator had maximum distance from the vehicle. General speaking, it is concluded that, more distance between operator and vehicle, more offset error of guidance. Although this developed system is applicable to many field operations, for precision works, especially where the field size is large, controlling through a PC based GUI program would be effective. Similarly, Liu et al. (2013) mentioned that, safety and performance of teleoperation systems can potentially be comprised, due to the cognitive limitations of the human operator and lack of complete information about the remote environment(Liu & Chopra, 2013). Instead, capturing image and transmitting terrain information to the farmer office and controlling through a PC, could simulate the operator in-the-cab situation, while the operator is protected from hazardous conditions, field vibration and noise.

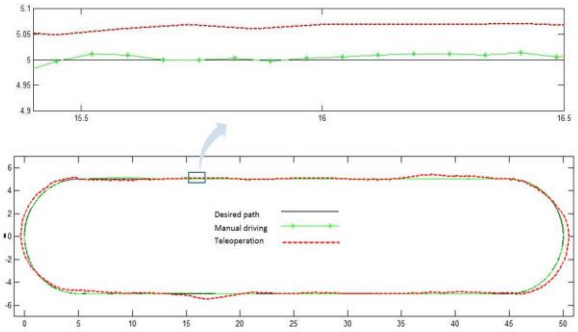


Figure 7. Comparison of the best teleoperation result with the third replication of manual mode at 2 km/h.

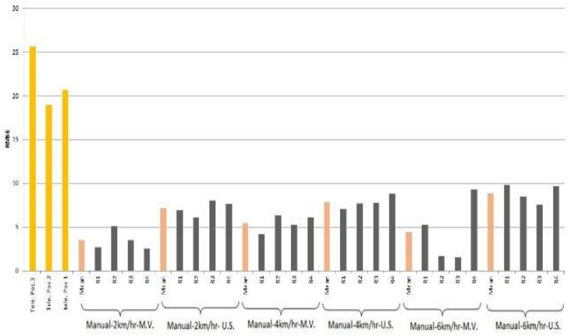


Figure 8. RMSE of all performed experiments.

4. Conclusion

The SAPHT, a renewable energy based tractor, was equipped with some autonomous guidance systems. Beside, controlling the developed system in a teleoperational mode, the system can also be used for conventional in-cab operation. The remotely controlled parameters were: velocity, forward/backward movement selection, steering, PTO activating and 3PH engagement. To evaluate accuracy of the developed system, the ASABE standard document X587 was used by some changes due to the existing limitations. Results showed that, in the teleoperational mode, increasing speed more than 2 km/h led to unacceptable results, so in this mode, the tests were carried out at 2 km/h and from three different positions. Data acquisition performed by means of ultrasonic sensor and a camera.

Experimental results showed that the RMSE of teleoperational mode is several times more than that of manually performed tests. In teleoperational mode, RMSEs of trajectories with respect to three different points were obtained to be about 19, 21 and 26 cm. Although, the system is applicable for many operations such as mowing, fertilization, however, the technique is recommended with caution for precision operations. For such operations controlling by a PC based GUI program would be effective. On the other hand, capturing the image and transmitting terrain information to the farmer office and controlling through a PC could simulate virtually the operator in-the-cab situation, while the operator is protected from hazardous conditions and field vibration and noise.

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توسعه یک روبات کنترل از راه دور و امکانسنجی استفاده از آن در عملیات کشاورزی

چکیده

در حال حاضر پیشرفت های زیادی در زمینه ماشین ها و روبات های کشاورزی به منظور افزایش بازدهی، کاهش استفاده از نیروی کار، جلوگیری از قرار گیری نیروی کار در شرایط سخت و خطرناک مزرعه، افزایش دقت در مراحل مختلف کشاورزی روی داده است. در این تحقیق به منظور امکانسنجی استفاده از روبات های کنترل از راه دور در کشاورزی و آزمایش دقت آن، ساخت که یک تراکتور الکتریکی بر مبنای انرژی های تجدیدپذیر است به امکانات کنترل از راه دور و حسگر های خودکار مجهز گردید و مورد آزمون قرار گرفت. ساخت توانایی عملیات بصورت معمول و رانندگی راننده روی آن را نیز بصورت همزمان دارا می باشد. آزمون ا بر اساس استاندارد X576 که توسط ASABE ارائه شده است انجام گردید. داده برداری با استفاده از حسگر فراصوتی و همین طور روش های مبتنی بر پردازش تصویر انجام گردید. با استفاده از نرم افزار متلب داده ها با یکدیگر مقایسه شده و ترسیم گردیدند. نتایج حاکی از خطای زیاد کنترل از راه دور در مقایسه با حالت دستی بود. در حالت کنترل از راه دور مقدار RMSE با توجه به موقعیت راننده ۱۹، ۲۱ و ۲۶ cm بدست آمد. در پایان نتیجه گیری شد با اینکه این سامانه برای بسیاری از عملیات های کشاورزی مانند کود پاشی و سم پاشی قابل کاربرد می باشد ولیکن برای عملیات دقیق کشاورزی نیاز به افزایش دقت احساس می شود.

کلمات کلیدی: کنترل از راه دور، انتقال هاف، هدایت از راه دور، روبات کشاورزی.