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Development of an intelligent master-slave system between agricultural vehicles

Xi Zhang, Marcus Geimer, Patrick O. Noack, Ludwig Grandl

***Abstract*—This paper presents a method to develop an intelligent master-slave system between agricultural vehicles, which will enable a semi-autonomous agricultural vehicle (slave) to follow a leading tractor (master) with a given lateral and longitudinal offset. In our study not only the follow-up motions but also the site-specific control of the apparatus such as rear and front power lift was considered. In the first part of this paper the recent research works in the area autonomous farming were discussed and the restrictions of these research works were illustrated. In the second part an approach to construct a master-slave system between two agricultural vehicles was demonstrated. In the next part the mathematic modeling of this master-slave system and the simulation results about the control algorithm were demonstrated. Afterwards the result of a real field test was presented and the safety considerations about such an intelligent vehicle system were made.**

I. INTRODUCTION

The agricultural farming industry is facing significant challenges at present. The global competition for a higher productivity in the agriculture has made demands on more cooperation between agricultural machines. The decreasing number of farming labor force and the higher labor costs in the agricultural industry is a significant issue for the European agriculture. As a response to mechanized and site-specific farming, more and more GPS-guidance is utilized in modern farming to meet the demands on precision agriculture and has made possible to guide the agricultural vehicles autonomously. For example, with the commercial real-time kinematic (RTK) GPS systems the accuracy of the positioning can reach 1 to 2 cm per 10 km [1].

In the past ten years, many research works have been carried out to develop an automated agricultural vehicle to replace the labor workforce in the farming operation. In [2] an automatic steering system was developed to guide a John Deere 7800 tractor along prescribed straight row courses with an average error of approximately 2 cm. In [3] a robot tractor was developed based on RTK-GPS and gyroscope to provide navigation information for the path tracking. Such field robot with auto-steering systems are capable of steering along target lines automatically, but the application of such autonomous agricultural vehicles can only be confined to a laboratory environment, where obstacles and other safety related problems could be foreseen.

To solve the safety problems in the real field operations many other high-tech sensors have been used to sense the surrounding environment of the farming vehicles. In [4] a machine vision based guidance system was demonstrated for an autonomous agricultural small-grain harvester using a cab-mounted camera. In the recent years laser or laser radar (ladar) have been more and more applied in autonomous vehicles to detect obstacles for the safety reasons. In [5] ladar has been used to navigate a small robot tractor through an orchard field. However most of the solutions have been successfully realized only in laboratory conditions. Field trials demonstrated that an automatic guided agricultural vehicle could assist the operator but could not completely replace the operator because of safety considerations. Some solutions which have been proved robust in field tests were very costly and still a long way from commercialization.

On such a background a master-slave system between agricultural vehicles can be regarded as an intermediate step on the road to completely autonomous agricultural vehicles. In this system the slave vehicle is able to follow the master vehicle and fulfill the same or different working processes such as plowing and seeding. Because of the presence of the operator on one of the agricultural vehicles, the safety of such a semi-autonomous system can be easily ensured without too much consideration about costly sensors and complicated sensor fusion algorithms.

The primary objective of this paper is to present a method to develop a master-slave system between agricultural vehicles, which will enable one unmanned tractor to follow up another leading tractor with a given lateral and longitudinal offset. This system can allow one operator to utilize more than two agricultural machines simultaneously, so that the productivity of the working process will be substantially improved and the competitiveness of the agriculture producer will be enhanced.

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X. Zhang is with the Institute of Vehicle Science and Mobile Machines, Karlsruhe Institute of Technology, Karlsruhe D-76131 Germany (phone: +49-721-608-8640; fax: +49-721-608-8609; e-mail: xi.zhang@kit.edu).

Professor M. Geimer is head of the Institute of Vehicle Science and Mobile Machines, Karlsruhe Institute of Technology, Karlsruhe D-76131 Germany (e-mail: geimer@kit.edu).

P. O. Noack is with the geo-konzept GmbH, Gut Wittenfeld, D-85111 Adelschlag, Germany. (e-mail: pnoack@geo-konzept.de).

L. Grandl is with the AGCO Corporation, Johann-Georg-Fendt-Str. 4, Marktoberdorf, D-87616 Germany. (e-mail: Ludwig.grandl@xfendt.de).

II. EQUIPMENTS AND METHODS

A. Equipments

Fig. 1 Fendt 936 Vario tractor and its cabin with machine guidance terminal

Fig. 1 shows one of the experimental agricultural vehicles, which was used to compose the master-slave system. The leading vehicle as well as the following vehicle is a 265 kW four-wheel drive Fendt 936 Vario model which is 5.65 m long, 2.75 m wide and 3.37 m high. The equipment used to measure the tractor position of the master tractor is different from the slave tractor. The master tractor uses a Trimble navigation system, which was mounted by the geo-konzept GmbH. With the AgGPS 252 GPS-receiver attached to the roof of the cab and the 450 radio equipment which receives the real-time kinematic (RTK) signals at 2 Hz data throughput rate, the position accuracy is less than 2.5 cm. Using data from the GPS receiver and internal sensors the position data can be further corrected by the navigation controller in the cab which can compensate the roll, pitch and yaw movement of the vehicle during measurement.

In the slave tractor an auto-guide system was already installed to measure the position of the vehicle. This system is an accessory equipment of the Fendt 936 Vario tractor and can correct the positioning error caused by the inclination of the ground. A gyroscope is also integrated in this auto-guide system, so that the position of the tractor can still be measured relatively accurately, even if no accurate GPS signals are received. Both tractors are equipped with an industrial computer which connects the GPS measurement unit and the tractor control unit. The industrial computer “AutoBox” is composed of a PowerPC 750GX processor board running at 1 GHz and several peripheral boards, which can communicate with external equipments over controller area network (CAN) or serial interfaces. With the real-time operating system running on the PowerPC, the AutoBox performs data collection, condition monitoring and control signal computations using software written at the Karlsruhe Institute of Technology.

B. Methods

In Fig. 2 a method to design a master-slave system between two tractors is demonstrated. A virtual towing bar is used here to demonstrate vividly the coupling between a leading tractor and another unmanned agricultural machine, which follows the leading one. Both vehicles will receive GPS signals to obtain their positions and a path segment (red) to guide the unmanned vehicle will be calculated from the trajectory of the leading tractor (blue) with a longitudinal and a lateral offset. The path segment to guide the unmanned vehicle will be transferred from the leading tractor to the following one periodically using wireless communication. A tolerance zone with a given width and length is conceived to restrain the following tractor from colliding to the leading one.

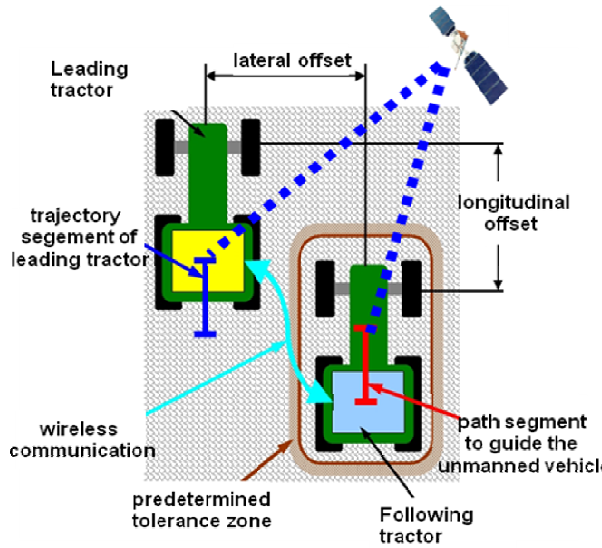

Figure 2: Schematic diagram of the towing bar system for two tractors using GPS navigation and wireless data exchange.

III. VEHICLE MODEL AND MOTION CONTROL

A. Vehicle Model

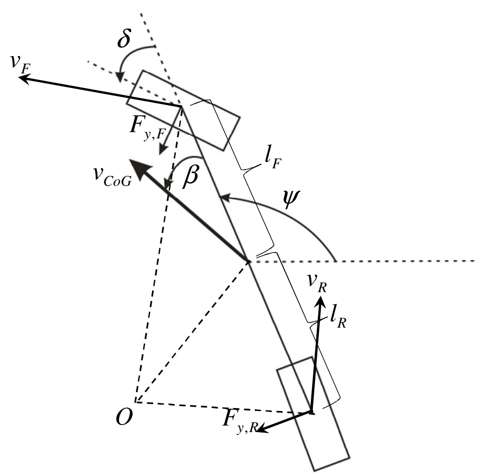

Figure 3: Dynamic model of the unmanned vehicle (Slave).

Under the basic assumptions of planar motion, rigid body and small slippage of the tire, the experimental vehicle can be approximated using a single track model [6], as shown in Fig. 3. Because of the small side-slip angle of the front and rear wheels, the lateral forces on the front and rear wheel can be calculated approximately as:

$$F_{y,F} = c_F \cdot \left(\delta - \beta - \frac{l_F \dot{\psi}}{v_{CoG}} \right)$$
$$F_{y,R} = c_R \cdot \left(\frac{l_R \dot{\psi}}{v_{CoG}} - \beta \right). \tag{1}$$

Considering both the yaw movement and the lateral acceleration of the vehicle, the dynamic model of the vehicle can be created using the following relations:

$$J \cdot \ddot{\psi} = l_F \cdot F_{y,F} - l_R \cdot F_{y,R}$$
$$mv\left(\dot{\beta} + \dot{\psi}\right) = F_{y,F} + F_{y,R}. \tag{2}$$

Combining the equations in (1) and the equations in (2) the vehicle dynamic model can be calculated as follows:

$$\ddot{\psi} = -\frac{c_F l_F^2 + c_R l_R^2}{J v_{CoG}} \dot{\psi} - \frac{c_F l_F - c_R l_R}{J} \beta + \frac{c_F l_F}{J} \delta$$
$$\dot{\beta} = -\left(\frac{c_F l_F - c_R l_R}{m v_{CoG}^2} + 1 \right) \dot{\psi} - \frac{c_F + c_R}{m v_{CoG}} \beta + \frac{c_F}{m v_{CoG}} \delta. \tag{3}$$

B. Reference Course Generation

The desired reference course to guide the unmanned tractor was calculated using the position data obtained from the GPS measurements on the leading tractor (Fig. 4). The solid curve, which is composed of a series of position points, refers to the trajectory of the leading tractor. On the other hand the dashed curve which is composed of a series of mapping points refers to the reference course of the following tractor. The mapping points is on the normal of the solid curve at the current positions of the leading tractor with a lateral offset of d. Point O is the common instantaneous turn center of the leading and the following tractor. The current curve radius of the leading tractor can be represented as:

$$\rho = \frac{v}{\dot{\beta} + \dot{\psi}} \tag{4}$$

The desired vehicle speed for the following tractor will be determined according to its turning radius and the current speed of the leading vehicle.

$$\rho' = \frac{v}{\dot{\beta} + \dot{\psi}} - d$$
$$v'_k = v_k \cdot \frac{\rho'}{\rho} \tag{5}$$

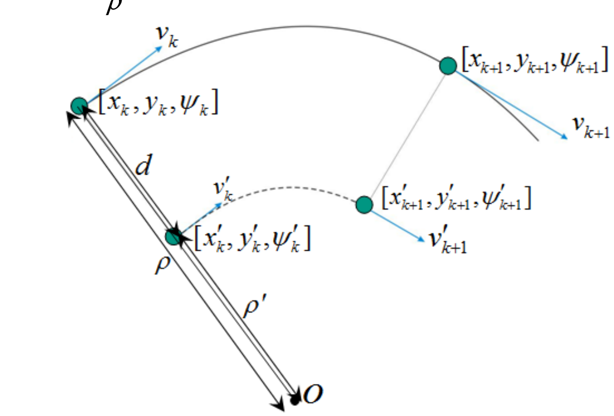

Figure 4: Trajectory of the leading tractor (solid curve) and desired path for the following tractor (dashed curve)

C. Tracking Controller

To guide the unmanned vehicle along the calculated path, a tracking controller must be designed so that the lateral offset of the vehicle to the desired reference course remains small. Besides the two state varialbes β and $\dot{\psi}$ representing the vehicle lateral dynamics, the lateral offset y should also be used as an additional state variable in the state space equations as:

$$\dot{y} = v_{CoG}(\psi + \beta - \psi_{ref}), \tag{6}$$

where ψ_{ref} is the track angle of the desired course .

In this case the state vector is extended to four state variables $[\dot{\psi}, \psi, \beta, y]$, namely the yaw angle and the yaw rate of the tractor, the side slip angle of the tractor and its lateral offset from the desired course. The track angle of the desired course is regarded as a measurable disturbance variable. Thus the whole tracking model can be written in state space as:

$$\underline{\dot{x}} = \underline{A} \cdot \underline{x} + \underline{b} \cdot u + \underline{e} \cdot z, \tag{7}$$

in which $\underline{x}$ stands for the vector of the four state variables, u stands for δ and z stands for ψ_{ref}. The output equation can be written as:

$$y = \underline{c} \cdot \underline{x} = [0\,0\,0\,1] \cdot \underline{x} \tag{8}$$

To guide the slave tractor along the reference course calculated from the master tractor trajectory a PD controller with state feedback and disturbance feedforward is designed (Fig. 5).

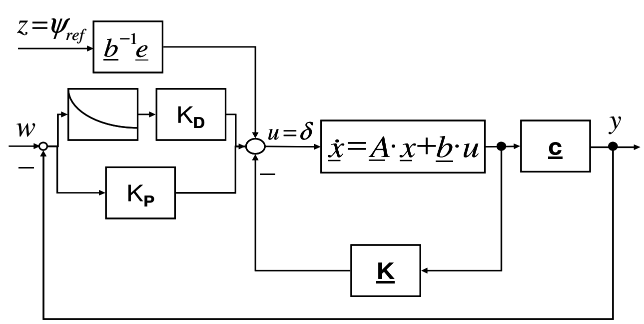

Figure 5: PD controller with state feedback and disturbance feedforward

D. Computer Simulation

In advance of the field test, the tracking-control performance was evaluated by computer simulation. Assumptions were made according to each situation. For example, in one computer simulation the steering angle of the master tractor increases from 0° to 3° at the time of 20 and decreases from 3° to 0° at the time of 24. After another 2 seconds the steering angle changes similarly in the opposite direction (Fig. 6).

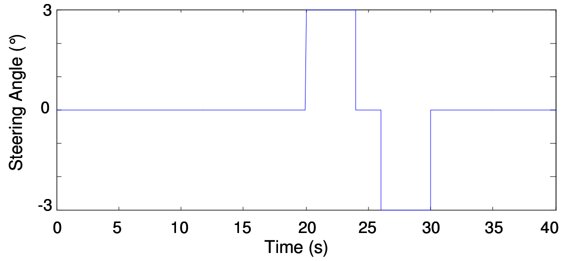

Figure 6: Steering angle change of the leading vehicle

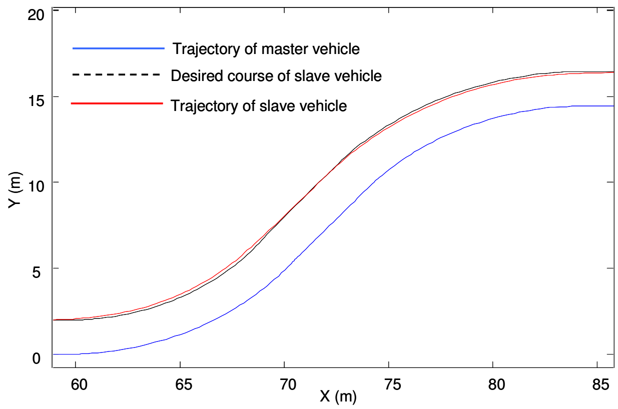

Figure 7: Simulation result of the tracking control (20s~30s)

Figure 7 shows the results of this simulation, in which both vehicles have change their lanes. The dashed curve is the desired reference course calculated from the trajectory of the master vehicle with a lateral offset of 2m. The red solid curve is the course which the slave vehicle actually takes to follow the master tractor. The simulation results indicate that the deviation between the reference course and the actual course of the following vehicle is less than 20cm, that means the maximal control error is less than 10%.

IV. WIRELESS COMMUNICATION

A. Hardware

One of the most important prerequisites for an electronic controlled master-slave vehicle system is that the leading and the following vehicles are connected by a so-called wireless CAN-bridge, which can collect the data from the controller area network (CAN) bus in one vehicle, transmit it over the air and send the information again to the CAN bus in the other vehicle. Because of the normally large acreage of a farm, a wide-coverage mobile communication device with real-time link ability must be chosen to satisfy the requirements for such an inter-vehicle communication [7].

For the radio interfaces the XBee-Pro wireless module from the company Maxstream serves as an IEEE 802.15.4 standard compliant chip. It operates at 2.4 GHz of the ISM radio band and can reach a theoretical data throughput of 250 kbps. Its large band width is sufficient for the transmission of all the navigation and control data defined in our data protocol every 100 milliseconds. With an outdoor range of 1.6 km, it enables a robust point-to-point connectivity in the line of sight.

B. Software

A data protocol, which defines the data type and frame format for all the information to be transmitted by the wireless module, has been created to distinguish communication data with different content and different priorities.

TABLE I
DATA PROTOCOL (POSITION DATA)

FIELD	BYTES	CONTENT(EXAMPLE)
Delimiter	1	0x FF
Frame-ID	1	0x 02
UTC	4	0x 23E7694
Latitude	6	0x 12318809C
Longtitude	6	0x 42C73654
Heading	2	0x 73D
Speed	2	0x 34
Direction	2	0x 71A
Date	4	0x 1EA82916
Reserved	3	Not defined
EOF	1	0xFE

Delimiter: Check byte for the start of a frame
Frame-ID: Identification for the data frame
UTC: Coordinated Universal Time
Latitude: Latitude of the current position of the leading vehicle
Longitude: Lontigutde of the current position of the leading vehicle
Heading: Angle where the leading vehicle is pointing compared to the true north
Speed: Velocity of the leading vehicle
Direction: Direction in which the leading vehicle is moving
Date: Date when the GPS information is recorded
EOF: Check byte for the end of a frame

In Table 1 the position data of the leading vehicle is defined in a data frame with 32 bytes and with a frame identifier (frame-ID) of 2. Its frame-ID indicates that this information has a relative higher priority in the whole data list. That reflects apparently the fact that the position data is very crucial for the safety of the following tractor. Without this information, the unmanned vehicle could not be guided correctly and there would be collision danger.

V. SITE-SPECIFIC FARMING

One of the novel properties of this master slave system is the site-specific management of farming process. During the farming process the unmanned slave tractor is able to operate its attached implements as well as the master tractor. Under certain circumstances the slave tractor should not copy the operations on the master tractor at the same time, but the operations on the master vehicle will be “stamped” with geographic coordinates and this operation will be only accomplished, when the slave vehicle arrives at the specific site where this operation should be carried out.
These site-specific operations were called as “geo events”. Among these “geo events”, which were implemented in our field tests, are the raising and sinking of the front and rear

power lifts, starting and stopping of the front and rear PTO shafts as well as the control of the three-point hitch of the tractor.

VI. Field Tests and Results

Verification tests were conducted on both asphalt and farm fields. The trajectory tracking results from a farm field test is shown in Fig. 8. In this test, the trajectory of the leading tractor was measured by the Trimble navigation system and transmitted through the wireless communication to the following tractor. This information as well as the information about the following tractor itself were recorded by CAN monitoring software and demonstrated in a UTM-coordinates-based map as shown in Fig. 8.

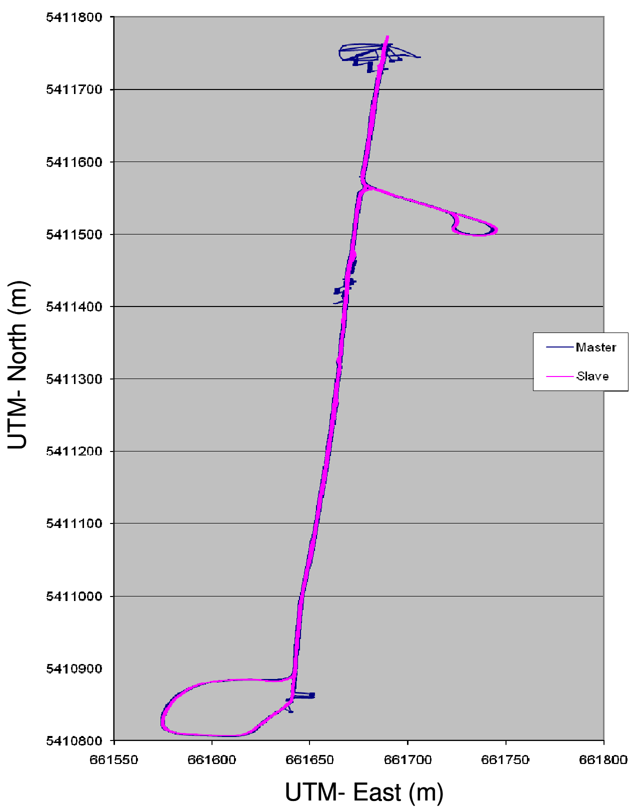

Figure 8: Tracking result from a field test

The results showed that the lateral deviation was less than 0.1m on most of the path trajectories. Larger deviations exist only on the path trajectories where inaccurate position measurements of the master vehicle were taken.

VII. Safety Considerations

A vital part of an autonomous, unmanned vehicle is safety. In such a towing bar system, the presence of the operator enhances the safety of the system in unexpected dangerous situations. To disburden the operator from the routine supervising work and assist him by decision making, programs doing condition monitoring have been integrated in the software.

One of the most important system monitoring is the distance monitoring. A virtual rectangle safety zone, which surrounds the unmanned following tractor during its moving, is conceived to constrain the movement of the tractor and to prevent it from colliding against the leading vehicle (see Fig. 2). When the following tractor goes beyond the constraints determined by this safety zone, it will be halted by a real-time program, which will steadily monitor the position of the unmanned vehicle.

Another safety related factor in the master-slave vehicle system is the wireless connection between the two tractors. A real-time thread in the system monitoring software sends periodically an “Alive” signal from the leading tractor to the following one. Absence of such information is indicative of a interrupt of the wireless connection and the real-time thread will halt all operations on the following tractor. As a backup of the supervising software the operator can trigger the emergency stopping to halt the following vehicle immediately in unexpected dangerous situations.

A key issue concerning the development of an electronic controlled, safety-related system is to determine the safety integrity level needed for all subsystems. Using the risk graph defined in the international standard IEC 61508 [8], the severity level of injury and the required performance levels can be derived when the corresponding subsystem fails. As an example, a risk assessment has been conducted for the wireless communication used in the master-slave system (Fig. 9). The break of the wireless communication can cause severe injury (S2), because without the information about the master vehicle the unmanned slave could not be guided correctly and there would be collision danger; the frequency of its exposure to hazard is relative high (F2) because of other interferences in the air; the possibility to avoid the hazard exits by triggering an emergency stopping when the acknowledgement for a successful data transmission cannot be obtained by the sender in a certain time period. Therefore the risk assessment of the wireless communication will take the red path in the risk graph. The result is the safety integrity level of 2 and a fail-silent performance is needed for this level. That means the whole system must be shut down, when this subsystem fails. Using a 1oo2D-architecture [8], the safety integrity level of the wireless communication can be enhanced to 3. That means the whole system can still work in fail-tolerant mode when a redundant wireless modem is used in this architecture.

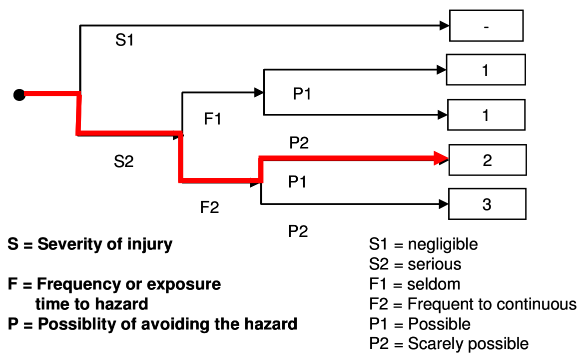

Figure 9: Classification of safety-related system in different safety-integrity-level according to IEC 61508

VIII. CONCLUSION

In this paper we presented an approach for developing an intelligent master-slave system for agricultural vehicles, which is able to automate an unmanned agricultural vehicle to fulfil some agricultural task, such as plowing and drilling, cooperatively with another leading tractor. Compared with other autonomous agricultural robots which are still far from commercialization, the experimental prototype will be able to be converted in a commercialized product in the near future. An interesting and novel facet of this research is the tolerance zone which constrains the movement of the autonomous vehicle. Significant challenges still lay ahead to determine the dimension of this tolerance zone and to control the unmanned vehicle accurately so that it can always stay in this tolerance zone. Another advantage of our proposal is the supervision of the operator as a safety back-up of the system. Preliminary results from our computer simulation and the field tests have shown that the following vehicle can follow the leading one satisfactorily.

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