Backward motion control of a mobile robot with *n* passive trailers

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Abstract: In this paper, it is shown how a robot with *n* passive trailers can be controlled in backward direction. When driving backward direction, a kinematic model of the system is represented highly nonlinear equations. The problem is formulated as a trajectory following problem, rather than control of independent generalized coordinates. Also, the state and input saturation problems are formulated as a trajectory generation problem. The trajectory is traced by a rear hinge point of the last trailer, and reference trajectories include line segments, circular shapes and rectangular turns.
Experimental verifications were carried out with the PSR-2(public service robot 2nd version) with three passive trailers. Experimental result showed that the backward motion control can be successfully carried out using the proposed control scheme.

Keywords: passive multiple trailers, backward motion, trajectory tracking, VLTM

1. INTRODUCTION

The PSR2 is under development at the KIST, towards various indoor service applications (see Fig. 1). Major target tasks include patrol, floor cleaning, luggage transportation and so forth. We have proposed a design scheme of the passive multiple trailer system, which showed excellent trajectory following performance [2]. Exploitation of passive trailers provides re-configurability which is advantages in practical applications. However, it is difficult to control the motion of a multi-body mobile robot system. A kinematic model is represented by highly nonlinear equations. There are only two velocity inputs for n+3 generalized coordinates. Moreover, the backward motion of the multiple trailer system is presented by unstable nonlinear equations.

For the past a decade, there are fruitful literatures for the control of trailer systems. Laumond[8] showed the controllability of a multiple direct-hooked(or standard) trailer system. Murray and Sastry proposed Chained form in [9], which provided the way to develop many controllers to steer and to stabilize nonholonomic systems, including the multiple trailer system. Typical examples are open loop strategies proposed by Tilbury, Murray and Sastry in [10] and a closed loop controller by Sordalen and Wichlund [11]. Rouchon et al. proposed an open loop motion generation strategy using a property of trailer, differential flatness [1]. Laumond proposed the virtual robot concept to control the backward motion of only one direct-hooked or off-hooked (or general) trailer [6]. Altafini proposed the hybrid controller for backward motion of general 3-trailer [5]. Nevertheless, little literature is available on the backward motion of a robot with multiple off-hooked trailers.

In this paper, it is shown how a robot with n passive trailers can be efficiently controlled in backward direction using one simple controller. The problem is formulated as a trajectory following problem, rather than control of independent generalized coordinates. Once a reference trajectory is given to the n'th trailer, then n'th trailer is controlled to follow a desired path within an acceptable error range. Then all the other connected trailers successively move along the trajectory of the n'th trailer. Kinematic model is iteratively defined between connected adjacent bodies. By using iterative kinematics and trajectory tracking aspects, a control problem can be simplified. From the advantageous kinematic design of the passive trailer systems, it can be shown that the trajectory of i'th trailer converges to the trajectory of i+1'th trailer. This fact implies that once the desired motion of the n'th trailer is obtained, appropriate motion of the pushing mobile robot can be computed easily. A feedback controller can be designed by monitoring the n'th trailer position and joint angles of hinge points. Therefore, the multi-body mobile system can be controlled to both directions.

Since the proposed controller is developed for general multi-axle robotic systems, many of the mobile robotic system can be controller by applying the scheme. For example, a kinematic model of a car-like vehicle with a trailer can be derived from the general multi-body kinematics. Therefore, control inputs of such systems can be obtained by appropriate coordinate and input transformation of the general kinematics. This is another significant advantage of the proposed scheme.

We begin with a hardware description of the PSR2 in Section 2. Section 3 constructs kinematic equations of the system. Backward motion controller and the virtual link tracking method (VLTM) are introduced in Section 4. Section 5 describes experimental results. Finally, we present some tentative conclusion and recommendations for further study.

Fig. 1 The PSR2 with trailers

3. KINEMATIC MODEL

The off-hooked trailer system is important here because it indicates that the system is not differentially flat [1] neither feedback linearizable, and so simple motion planning techniques, like those based on algebraic tools cannot be applied.

Let x_0, y_0 be the Cartesian coordinates of the robot reference point, θ_0 the robot orientation with respect to the X axis, and θ_i the absolute angle of i-th trailer (see Fig.2). The front link and rear link length are F, R, respectively. These constants defining the geometry of the robot-trailer connection. When $R_i/F_i=1$, it is showed the trajectory tracking error is minimum in [2]. Therefore, we assume the condition. And if $R=0$, the connection is direct-hooked. In the direct-hooked trailer system, the front link of the trailer is hitched on the middle of wheel axis of the robot or trailers. That is, the direct-hooked system is a special case of off-hooked system. However, the properties are different from a control point of view and the systems are studied separately. The robot linear and angular velocities are v_0, ω_0 , respectively. Then the kinematic model of the system can be written as

$$\begin{aligned} \dot{x}_0 &= v_0 \cos\theta_0 \\ \dot{y}_0 &= v_0 \sin\theta_0 \\ \dot{\theta}_0 &= \omega_0 \end{aligned} \tag{1a}$$

$$\dot{\theta}_i = \frac{(-1)^{i-1}}{F_i}(v_0 \sin\psi_i - \dot{\theta}_0 R_0 \cos\psi_i) \tag{1b}$$

where $\psi_i = \sum_{n=1}^{i}(-1)^{n-1}\varphi_n$, $\varphi_k = \theta_{k-1} - \theta_k$ and i, $k=1,...,n$. φ_k is relative angles which is measured directly from equipped potentiometers on the hitching point between k-1'th and k'th trailer. If R_i is not equal to zero, Eq. (1b) is invertible. The system configuration is $\mathbf{P} = (x_0, y_0, \theta_0, ..., \theta_n)$ and its derivative is $\dot{\mathbf{P}} = (\dot{x}_0, \dot{y}_0, \dot{\theta}_0, ..., \dot{\theta}_n)$. The input robot velocities v_0, ω_0 are subject to the constraints:

$$|v_0| \le v_{\max}, |\omega_0| \le \omega_{\max}, |\dot{v}_0| \le \dot{v}_{\max}, |\dot{\omega}_0| \le \dot{\omega}_{\max} .$$

These constraints ensure the absence of lateral slipping of the wheels. And the maximum velocities $v_{\max}, \omega_{\max}$ and accelerations $\dot{v}_{\max}, \dot{\omega}_{\max}$ are slightly small(0.1m/s, 0.1rad/s, 0.1m/s^2, 0.1rad/s^2), it is to make all the dynamic effects negligible.

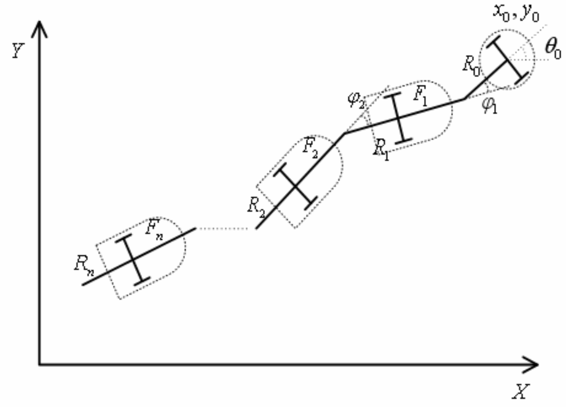

Fig. 2 Kinematic model

4. BACKWARD MOTION CONTROL

4.1 Virtual Link Tracking Method (VLTM)

The tracking control method for a non-holonomic mobile robot is reported in many literatures. Representative works are Kanayama's method [4] and Samson's method []. Both methods are 3 dimensional problem, robot position and orientation. However, the VLTM is 2 dimensional problem. The virtual hinge link is aligned with the robot heading direction or the opposite direction. If the link aligned with the heading direction, a robot position would converges to the trajectory by moving forward motion. And if opposite, the robot move to backward. The link length L is an important constant. The magnitude of L decides an offset from trajectory to robot position and angular velocity. $\tilde{x}_e, \tilde{y}_e$ is the error position between a desired position of the hinge point x_d, y_d and a current hinge position x_h, y_h in the Cartesian coordinate(see Fig. 3). Then, a robot linear and angular velocities v_r, ω_r are as following

$$\begin{aligned} \tilde{x}_e &= x_d - x_h \\ \tilde{y}_e &= y_d - y_h \\ v_r &= \tilde{x}_e \cos\theta_r + \tilde{y}_e \sin\theta_r \\ \omega_r &= (-\tilde{x}_e \sin\theta_r + \tilde{y}_e \cos\theta_r)/L \end{aligned}$$

where θ_r is a orientation of the robot. If the hinge point is located at the behind of the wheel axis, L is replaced $-L$.

$$\begin{pmatrix} \dot{x}_r \\ \dot{y}_r \\ \dot{\theta}_r \end{pmatrix} = \begin{bmatrix} \cos\theta_r & 0 \\ \sin\theta_r & 0 \\ 0 & 1 \end{bmatrix} \begin{pmatrix} v_r \\ \omega_r \end{pmatrix}$$

This tracking method is exponentially stable.

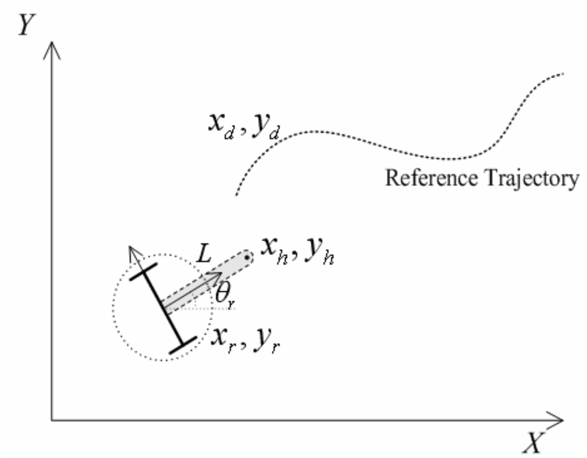

Fig. 3 modeling a robot to a trailer

4.2 Backward motion control of trailer system

We proposed the VLTM in previous part. The method can be directly applied to backward motion of a trailer system. We can replace a virtual robot, which has a virtual link at the behind of wheel axis, by the last trailer. Then, the robot traces the trajectory by backward motion. The robot velocities are the desired velocities v_n, ω_n of the last trailer. These velocities are connected with real robot velocities v_0, ω_0 by a one-to-one mapping as following.

$$v_0 = v_n \cos\psi_n + \frac{F_n}{(-1)^{n-1}}\dot{\theta}_n \sin\psi_n$$

$$\omega_0 = \dot{\theta}_0 = \frac{1}{R_0}(v_n \sin\psi_n - \frac{F_n}{(-1)^{n-1}}\dot{\theta}_n \cos\psi_n)$$

In Fig. 4, (x_d, y_d) and (x_c, y_c) are a reference position and a current position of the hinge point of the virtual robot, respectively.

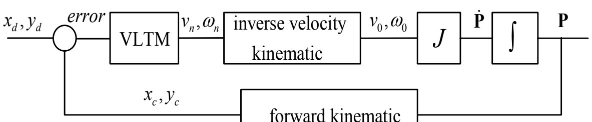

Fig. 4 Architecture of proposed tracking control method

2. PSR2 AND TREE TRAILERS

The PSR2 (see Fig.1) is composed of an omni-directional wheeled mobile platform, but we drive the robot, like a differential wheeled robot. Two SICK laser scanners located at front and behind of the wheel axis gather information for environment. Two PB-9 infra-red range sensors are mounted at both sides. The information of environment is for localization and for detecting obstacles. 4 CCD cameras which have a web server and a pan/tilt camera are equipped on the top of the robot for the task patrol. The vision of the cameras are monitored and controlled remotely. Each trailer has two passive wheels and two casters. The passive wheel axis is located at the middle of front and rear hitching points, since the trajectory tracking error between a robot or a preceding trailer trajectory and a next trailer is most small[2]. The Joint angles are measured using three potentiometers which are connected with king-pins by flexible couplers.

5. EXPERIMENT AND CONCLUSION

Experimental verification is performed for two trajectories, a straight line and a circle. Each trajectory is sampled 0.01m interval.

Each experiment is proceeded as follows. The PSR2 get current position of the robot using the laser scanners. The scanners are located at front and behind, respectively. The trailers positions are measured from potentiometers. These potentiometers have analog outputs. The outputs are converted to 16-bit digital data by ACC-28E (accessory of the UMAC). The error in the relative angles is about 2-3 degrees, due to flexible coupler which make connection between kingpin and potentiometer axis. The link parameters R_i, F_i are 0.52m. The trajectories are predefined on global Cartesian coordinate. Then, we calculate the error position of the last trailer hinge.

Fig. 5-10 show the experimental and simulation results. The simulations have same condition and the initial configurations of the real system. Fig. 5 and Fig. 8 represent linear and angular velocities v_0, ω_0. There are small oscillations in angular velocity plot, due to measuring joint angle error. Fig. 6 and Fig. 9 represent relative angles. These angles converge to constant values. In circular path, the values converge to about 0.5rad and, in another case, converge to zero. Fig. 7 and Fig. 10 plot system movements. The black solid line is a reference trajectory and the blue dotted line is the trace of the robot.

6. CONCLUSION

It is shown that the backward motion of a mobile robot with passive multiple trailers can be controlled successfully. A kinematic parameter design is established, then backward motion controller is developed based on the trajectory following performance of the trailers. Since the multi-body system can be controlled to both direction, the system can navigate narrow corridors in practical applications. Furthermore, the proposed controller can be applied to many other classes of multi-axle mobile robotic systems, owing to its generality of kinematics. For example, a car-like vehicle can be interpreted as a mobile robot with single trailer.

Although many of the research outputs have been accumulated for the two wheel differential type mobile robot, there are fundamental limitations. It is difficult to navigate in irregular ground conditions with a two wheel differential type robot. Furthermore, dynamic stability cannot be guaranteed for the case of high-speed navigation. In order to deal with those drawbacks, multi-axle mobile robot is preferable, if appropriate motion control strategy is available.

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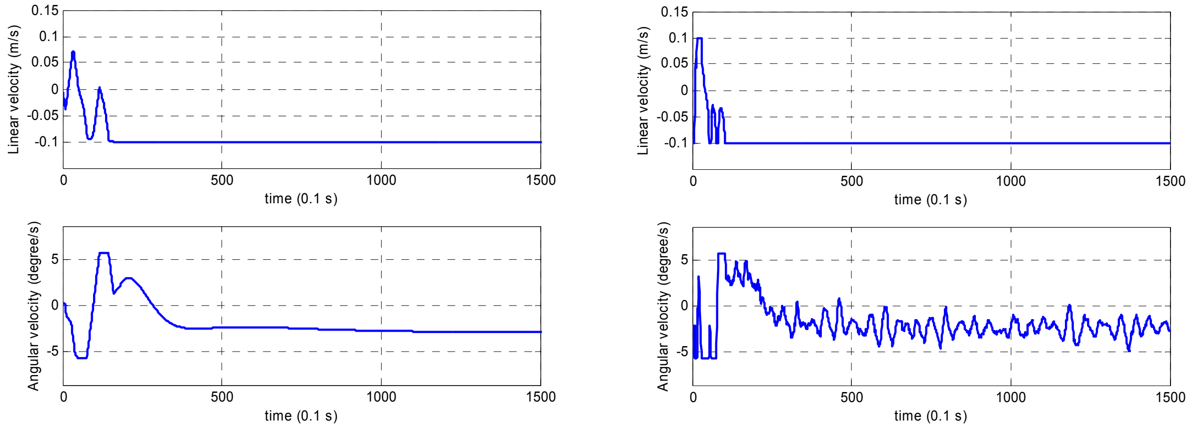
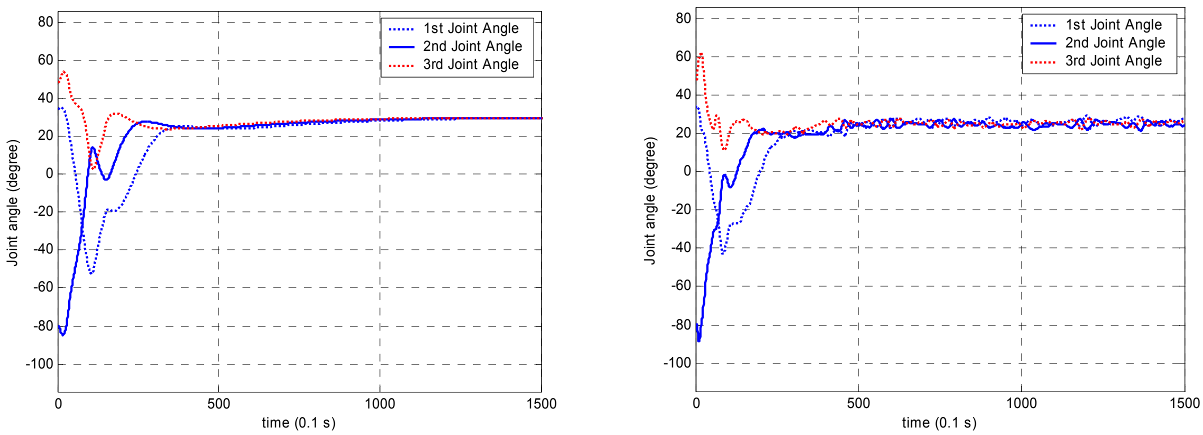


(a) simulation result (b) experimental result

Fig. 5 Linear and Angular velocities of the PSR2



(a) simulation result (b) experimental result

Fig. 6 Relative angles between trailers

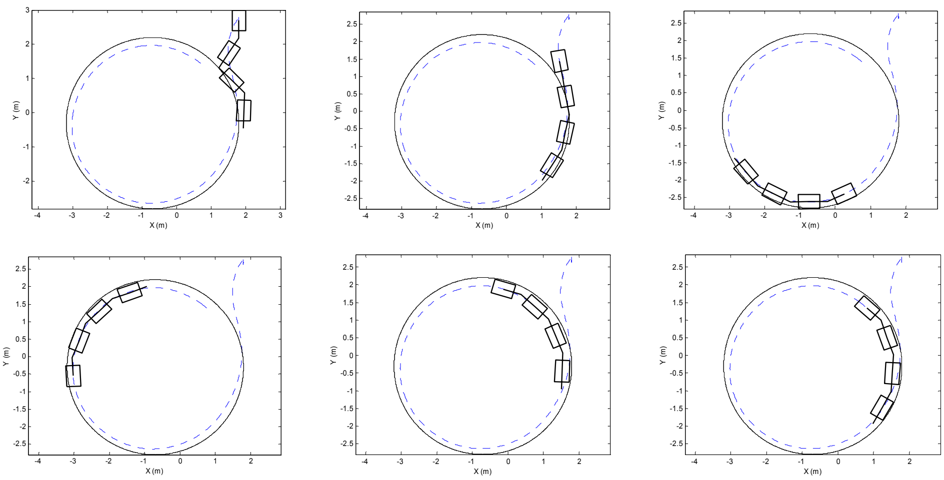
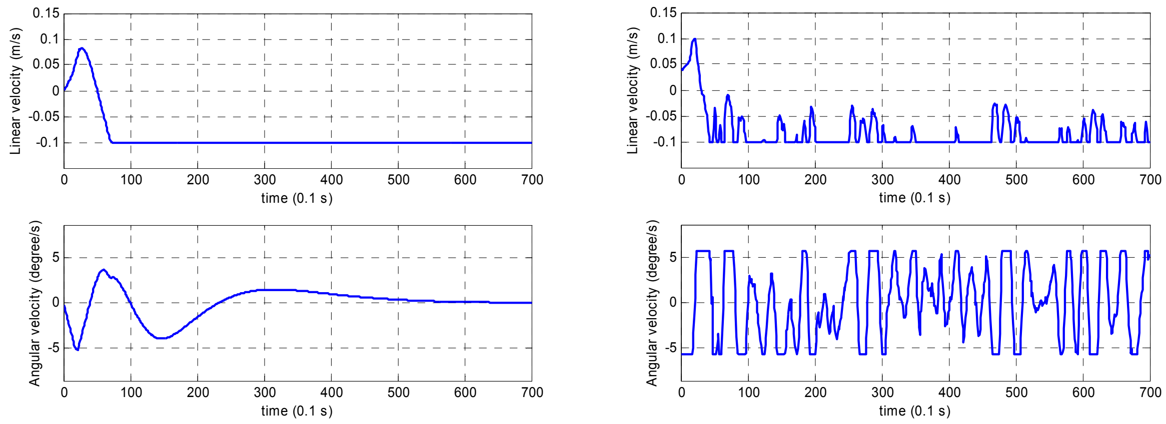
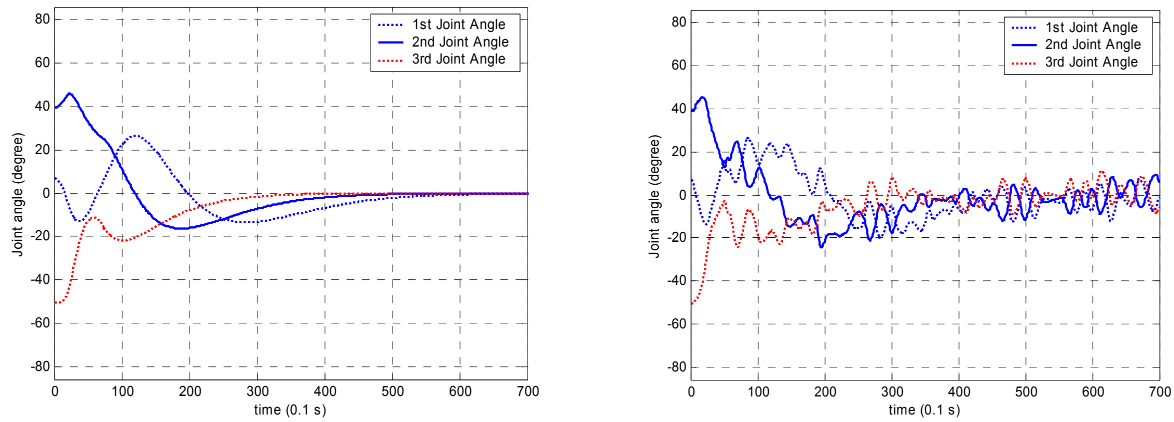


Fig. 7 Experimental result : a Circle path (radius = 2.5 m)



(a) simulation result (b) experimental result

Fig. 8 Linear and Angular velocities of the PSR2



(a) simulation result (b) experimental result

Fig. 9 Relative angles between trailers

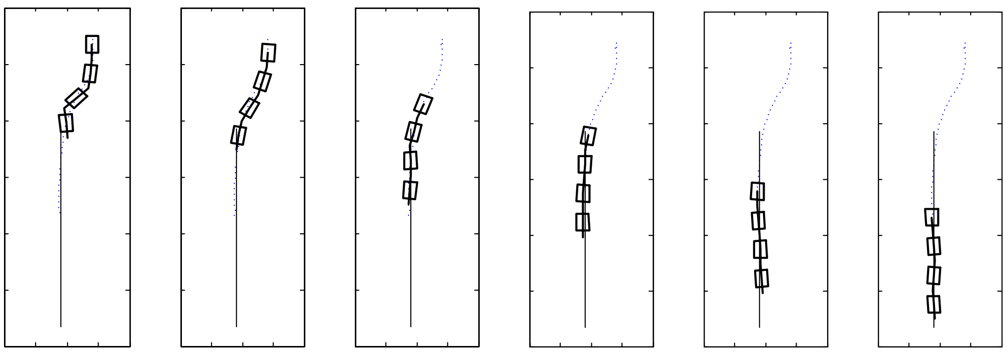


Fig. 10 Experimental result : a straight line path