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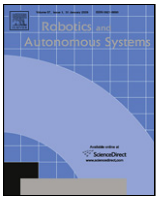

Modeling of tracked mobile manipulators with consideration of track–terrain and vehicle–manipulator interactions

Yugang Liu, Guangjun Liu *

Department of Aerospace Engineering, Ryerson University, Toronto, Ontario, Canada, M5B 2K3

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ABSTRACT

This paper presents a systematic method to establish the kinematics model for a tracked mobile manipulator on firm grounds, with consideration of the interactive motions between the tracks and the terrain, as well as those between the tracked vehicle and the onboard manipulator. Kinematics analysis is essential for real-time pose estimation and online autonomous navigation of tracked mobile manipulators. Furthermore, to improve the effectiveness of motion planning, and to simulate or control tracked mobile manipulators, a reliable kinematics model is required. However, kinematics modeling for a tracked mobile manipulator is complicated by the fact that there are infinite number of contact points between the tracks and the terrain, which makes slippage unavoidable. The track–terrain and vehicle–manipulator interactions make the problem even more complicated as the motion of the onboard manipulator and the centrifugal forces during moderate or high speed motion give rise to transfer of the load distribution, which will affect the longitudinal and lateral tractive forces and the resistance. Also, the motion of the mobile platform contributes to the inertial forces of the manipulator, and the track–terrain interactive forces help balance the gravity as well as the manipulation forces. The developed kinematics modeling approach is presented on the basis of a tracked mobile manipulator in our laboratory, but the forward kinematics analysis method, and the track–terrain and vehicle–manipulator interaction analysis algorithm are general, and can be used for any tracked mobile manipulators with little modification. This work lays a solid foundation for autonomous control, online slippage estimation, real-time traction optimization as well as tip-over prediction and prevention of tracked mobile manipulators.

1. Introduction

Tracked vehicles have attracted attention from numerous researchers for many years since they have substantial potential applications, such as mining, logging, farming, earth moving, planetary exporting, antiterrorist fighting, searching and rescuing. Tracked vehicles provide better floatation and traction than wheeled ones because they have larger contact area, which makes them suitable for off-road terrains [1]. However, this characteristic also makes slippage unavoidable, which then increases the complexity of kinematics and dynamic modeling.

At the early stage of tracked vehicle research, military vehicles such as tanks were given extensive attention [2] and the mechanics of vehicle–terrain interaction, which is known as terramechanics, was a sensitive topic [3,4]. Nowadays, robots are getting closer to human beings, and many light-weight tracked vehicles are developed for civilian purposes, which are designed to be able to change the track configuration to adapt to uneven terrains, so as to pass through obstacles or climb stairs [5–10]. Steerability analysis is always a concern [11–16] and a number of methods are proposed to accomplish steering of tracked vehicles, among them articulated-steering [12,13] and skid-steering [14–16] are the most popular techniques. Recently, the advancement in microprocessor technologies has stimulated researchers' interests in modeling, simulation and control of tracked vehicles. Some other recent research trends include the study on detracking phenomenon [17], and the investigation about the effects of initial track tension on soft ground mobility of tracked vehicles [18].

In related research works, many experiments have been conducted and reported on the behavior of tracked vehicles at various unprepared terrains [3]. The modular robot concept is introduced for the design and dynamic modeling of tracked vehicles [7,19]. A general theory for the mechanics of skid-steering on firm ground is developed and kinematics was analyzed for a steady-state turning maneuver [14]. Dynamic simulations are carried out for tracked vehicles with consideration of track–terrain and track–wheel interactions [20]. Newton–Euler formation is introduced to establish the dynamic model for multi-body tracked vehicles [21], in which the chassis, the rollers, the sprockets, the idlers and even all the links for tracks are modeled as separate elements. Extended

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* Corresponding author. Tel.: +1 416 979 5000; fax: +1 416 979 5056.
E-mail addresses: ygliu@ryerson.ca, gjliu@ryerson.ca (G. Liu).

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Kalman filter is employed to identify the slip of the tracks over terrain for tracked vehicles [22]. To improve motion control and pose estimation of tracked vehicles, a kinematics modeling approach is proposed and genetic algorithms are utilized to identify the instant rotation centers [23,24]. Considerable progress has been made in the development of analytical frameworks for evaluating and predicting tracked vehicle mobility over unprepared terrain, as highlighted in [25]. Tracked vehicles are treated as dynamic nonholonomic systems, and nominal forces are calculated to drive the tracked vehicle moving on a horizontal plane along specified paths and at desired speeds [26]. To control tracked mobile robots following desired paths, a hybrid approach is presented [27], which is composed of an adaptive controller utilized to reduce systematic external error, and a cross-coupling controller employed to suppress internal error. A device, called 'Encoder Trailer', was developed for improving position and orientation estimation of tracked mobile robots [28]. A tracked vehicle was modeled as a two input and two output system, and a robust turning controller has been designed on the basis of quantitative feedback theory [29]. A workspace path planner, a fuzzy logic path-tracking controller, a cross-coupling controller and a vision-based slip controller collaborate to realize point to point control of a semi-autonomous tracked mobile robot [30]. A kind of all-purpose tracked mobile platform was developed for exploring natural environments [31].

A tracked mobile manipulator integrates a tracked vehicle with an onboard manipulator. The onboard manipulator is employed to perform some definite operations and the tracked vehicle is utilized to carry and support the manipulator. This combination extends workspace and scope of applications of the entire robot dramatically. However, formulating the kinematics model for such an integrated structure is a challenging task due to the track–terrain interactions and the interactive motions between the tracked vehicle and the onboard manipulator. Considerable research has been reported on modeling, simulation and control of wheeled mobile manipulators [32–36], but few on tracked mobile manipulators. Most of the investigations on tracked vehicles were performed in terms of linear or circular motions at constant speeds, but few on nonstationary motion analysis, and even less on the general motion of tracked mobile manipulators.

This paper presents a general kinematics modeling approach, aiming to lay a solid foundation for automatic control of autonomous tracked mobile manipulators, which will improve the effectiveness of real-time pose estimation and online autonomous navigation. A systematic method is established to formulate the direct and inverse kinematics models of a tracked mobile manipulator moving on firm grounds. The interactive motions between the tracks and the terrain, as well as those between the tracked vehicle and the onboard manipulator, have been taken into account in the proposed method, and its effectiveness has been demonstrated with simulation results.

The rest of this paper is organized as follows: direct kinematics is analyzed in the next section. In Section 3, inverse kinematics is derived with consideration of track–terrain and vehicle–manipulator interactions. To demonstrate the applications of the proposed algorithm, simulations are conducted on a real tracked mobile manipulator in Section 4. Concluding remarks are given in the last section.

2. Direct kinematics analysis

The tracked mobile manipulator analyzed in this paper is as shown in Fig. 1. The platform is a light-weight tracked vehicle, which is composed of the chassis, two tracks, two driving wheels, two supporting wheels and two planetary wheels. The two driving wheels can be controlled independently to realize steering, and the two planetary wheels are driven by the same motor to ensure synchronization of the two tracks when configuration changes are necessary for passing through obstacles or climbing stairs.

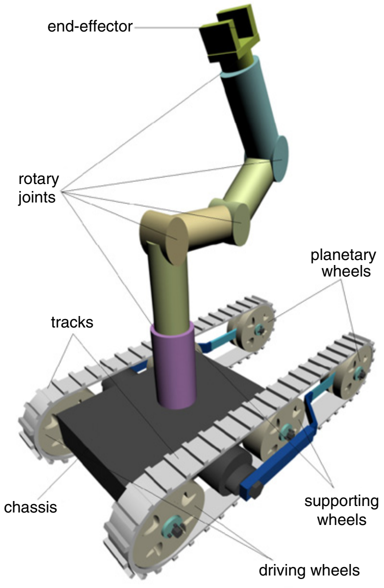

Fig. 1. A tracked mobile manipulator.

In this paper, we study the tracked mobile manipulator moving on a firm horizontal plane, but obstacle avoidance and stair climbing are beyond the scope of this paper. So the planetary wheels are extended and locked, and they can be modeled as supporting wheels. The mobile platform is assumed to be symmetrical with respect to $X_mO_mZ_m$, as shown in Fig. 2. The onboard manipulator is assumed to be composed of n rotary joints and an end-effector. This paper does not investigate detracking of the mobile platform, so the lateral slippage of the left and right tracks can be assumed to be consistent. Furthermore, it is assumed that the tracks cannot stretch and there is no slippage between the driving wheels and the tracks.

The motion of the tracked mobile manipulator during a time interval $[t^i\ t^{i+1}]$ is as illustrated in Fig. 2. An arbitrary inertial base frame $O_B-X_BY_BZ_B$ is fixed on the motion plane, while $O_m-X_mY_mZ_m$ is a frame on the mobile platform. In frame $O_m - X_mY_mZ_m$, the coordinate plane $X_mO_mY_m$ is defined as parallel to $X_BO_BY_B$, passing through the axes of all the wheels; the origin O_m is selected as the projection of the vehicle–manipulator contact point on $X_mO_mY_m$; and O_mX_m is chosen to be along the heading direction of the mobile platform. Then, kinematics of the mobile platform can be determined by the position $O_m(x_m, y_m)$ and the heading angle ϕ_m.

Let $\Delta t = t^{i+1} - t^i \to 0$, from Fig. 2, we can obtain

$$\begin{aligned}
&\Delta x_m = x_m^{i+1} - x_m^i = |O_m^iO_m^{i+1}| \cdot \cos(\phi_m^i + \alpha^i) &&\text{(a)}\\
&\Delta y_m = y_m^{i+1} - y_m^i = |O_m^iO_m^{i+1}| \cdot \sin(\phi_m^i + \alpha^i) &&\text{(b)}\\
&\Delta \phi_m = \phi_m^{i+1} - \phi_m^i = \gamma &&\text{(c)}
\end{aligned} \qquad (1)$$

where $|O_m^iO_m^{i+1}|$ is the distance between O_m^i and O_m^{i+1}.

In Fig. 2, the point O acts as instant center of rotation (ICR) for the tracked mobile manipulator in the short time interval. It is known that the ICRs for the tracked vehicle, the left track and the right track must lie on the same line, which is parallel to O_mY_m [23]. Since A_c, A_l and A_r are situated on the line connecting the ICRs, the instant velocities of these points are along the heading direction of the mobile robot, which means the side slippage during this time interval along OA_c is zero, i.e., $|OA_c^i| = |OA_c^{i+1}|$, $|OA_l^i| = |OA_l^{i+1}|$ and $|OA_r^i| = |OA_r^{i+1}|$. Then, the advances of A_c, A_l, A_r and the angles α^i, β^i can be calculated by