Automatic navigation of agricultural vehicles, such as tractors and harvesters, can increase the level of automation in the agricultural process, thereby lessening the human workload [1], [2]. In the agricultural environment, where vehicles move on uneven terrain, achieving maneuverability and mobility can be difficult, particularly when the path curvature is small or vehicle orientation and path tracking must be independently controlled.

To obtain the desired maneuverability and mobility, one approach is to individually actuate the drive and steering functions of each wheel on a four-wheeled vehicle. Figure 1 shows a prototype system for agricultural purposes. Figure 2 shows a vehicle schematic and block diagram model for closed-loop control of the steering and driving motors. For sensing and navigation, this prototype vehicle uses a combination of machine vision, a differential global positioning system (DGPS), and an inertial measurement unit (IMU). The focus of this work, however, is on path-following control. Although the vehicle is highly maneuverable due to its eight independent actuators, precise control is difficult due to the overconstrained nature of the actuation. It is challenging to coordinate all of the motors to avoid wheel slippage [3] as well as to precisely control the vehicle’s motion in both translation and orientation.

DETERMINATION OF CONTROL INPUTS

Analysis of the rigid-body velocity is used to determine the instantaneous control values for all of the motors. Assuming that the vehicle is a rigid body, the absolute velocity vector for each wheel is the sum of the translational and rotational velocity vectors with respect to the geometric center. The vehicle has
four wheels that are individually driven and steered, thereby making it omnidirectional. Unlike other agricultural navigation platforms, the vehicle can perform motions that are either purely translational or purely rotational. We first analyze the translational velocity and rotational velocity vector for each wheel as shown in Figure 3 and then study the composition of these velocity vectors as shown in Figure 4.

During purely translational motion, the longitudinal directions of all four wheels are oriented identically with respect to the vehicle body, and all four wheels spin at the same rate. Therefore, as shown in Figure 3(b), all of the wheel centers, and thus the geometric center of the vehicle body, move at the same velocity.

For purely rotational movement, the longitudinal axis of each wheel is oriented at either $45^\circ$ or $-45^\circ$ with respect to the orientation of the vehicle body, as shown in Figure 3(a). Due to the geometry of the vehicle, the velocity orientation of each wheel center is perpendicular to the line between the vehicle geometric center and the respective wheel center. Since all of the wheels are commanded to rotate at the same angular velocity, the vehicle rotates as a rigid body around its geometric center. Consequently, the vehicle’s turning radius is zero, giving the vehicle maneuverability that is superior to most two-wheel-steered agricultural vehicles.

ANALYSIS

We now combine the individual wheel translational and rotational motions to obtain the orientation and velocity of the vehicle as a whole. Figure 4 shows the translation (green) and rotational velocity vector (red) of each wheel center. Additionally, illustrated by the red vectors is the sum of the translational and rotational velocity vectors for each wheel. For each wheel, it follows that

$$u_c = u_t + u_r,$$

where $u_c$, $u_t$, and $u_r$ denote the total velocity vector, translational velocity vector, and rotational velocity vector of the wheel, respectively. Assuming no slip, the translational velocity of each wheel equals that of the vehicle, both of which are denoted by $u_t$. In addition, $u_r$ is given by

$$u_r = r \times \omega,$$

where $r$ is the vector from the instantaneous center of rotation (ICR), illustrated by the yellow circle of the vehicle in Figure 4, to the wheel itself, and $\omega$ is the angular velocity of rotation for the vehicle. Here, $\beta_r(t)$ represents the angle of the vector $u_c$ with respect to the x-axis of a global reference frame, and $\omega_r(t)$ denotes the length of the vector $u_r$.

The control inputs for the steering and driving motors $U_{st}(t)$ and $U_{ad}(t)$ are computed using proportional-integral-derivative (PID) control laws.

FIGURE 3 Rotational and translational motion. (a) Rotational motion. Each wheel is oriented $45^\circ$ or $-45^\circ$ with respect to the vehicle body, and all four wheels spin at the same rate. The vehicle body thus rotates around its geometric center at a fixed rate with zero turning radius. (b) Translational motion. Each wheel is oriented at the same angle with respect to vehicle body and the global reference frame, and all four wheels spin at the same rate. Thus, the vehicle body translates in the global reference frame without a change of attitude.

FIGURE 4 Velocity decomposition for all wheels. For each wheel, the pink vector represents the rotational component, the green vector describes the translational component, and the red vector is the composition of these velocities as a result of the parallelogram rule.

FIGURE 5 Vehicle motion along the reference path (ABCDE). The geometric center, represented by the red dot, tracks the reference path exactly. The attitude of the vehicle changes gradually throughout the path-following task.
\[ U_{as}(t) = K_{PS}\beta_e(t) + K_{DS} \frac{d\beta_e(t)}{dt} + K_{IS} \int_0^t \beta_e(t) dt \]  
\[ \text{and} \]
\[ U_{ad}(t) = K_{PD}\omega_e(t) + K_{DD} \frac{d\omega_e(t)}{dt} + K_{ID} \int_0^t \omega_e(t) dt, \]

where \( K_{PS}, K_{DS}, K_{IS}, K_{PD}, K_{DD}, K_{ID} \) are gains. In addition, \( \beta_e(t), \omega_e(t) \) are the errors between the reference variables \( \beta_r, \omega_r \) and the feedback measurements \( \beta_f, \omega_f \), given by

\[ \beta_e(t) = \beta_r(t) - \beta_f(t) \]
\[ \omega_e(t) = \omega_r(t) - \omega_f(t). \]

Figure 5 shows the attitudes of the wheels and the vehicle at various locations along a reference path. Note that the planar motion of the vehicle consists of translational and rotational motion. While translational motion moves the geometric center precisely along the reference path from A to D, the commanded rotational motion changes the vehicle orientation with respect to the path in a gradual and smooth fashion. From D to E, the planar motion of the vehicle consists only of translational motion since no vehicle rotation is needed.

Figure 6 shows the reference values for the front right wheel from A to D in Figure 5. Both curves of the wheel’s driving speed and steering angle are changed gradually with no abrupt variation during this segment. Since the movement is slow, only minimal wheel slippage can occur.

**AVOIDANCE OF SLIPPAGE**

Synchronization among the four wheels’ steering references plays an important role in their coordination. Figure 7 describes command execution state curves for the four steered wheels during a maneuver. PID speed-control algorithms are applied to the four driving motors with parameters that are different from the steer-control algorithms. When all four wheels are steered at the proper angles and precisely driven, the slippage of wheels can be minimized. However, when one wheel does not follow its steer reference command, for example, due to an environmental obstacle, large wheel slippage can occur, and the motion of the vehicle is difficult to estimate. A similar slippage problem occurs when the wheel speed references are not tracked precisely. To solve this problem, we allow the steering and drive controllers to actively report execution states of the steering commands to the upper navigation algorithm through the
vehicle CAN bus. The navigation algorithm waits for the reports. If the steering commands are executed correctly and in a timely manner, the drive commands are sent as usual. If a timeout report is received, the navigation algorithm calls other function modules to handle this situation, during which the information from the IMU, machine vision, and AGDGPS132 are fused.

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REFERENCES

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Robo Armwrestler
CHUL-GOO KANG

A n arm-wrestling robot called Robo Armwrestler (Figure 1) has recently been developed in our Intelligent Control and Robotics Laboratory to benefit the health care of senior citizens. The motivation for this project, which is supported by the Korean Government, is to reduce social welfare costs and to improve the quality of life of the elderly population by meeting their physical and mental needs. In recent decades, Korea’s aging population has increased by 35%, well over the standard 30% for an aging society. Our vision is to realize humanoid robots that have entertaining functions such as arm wrestling and chess playing, as well as service functions such as errands. Over time, we hope the robot will help both the elderly and the disabled.

Several years ago, Y. Bar-Cohen issued a challenge to build a robot using muscles of electrically activated polymers that could arm wrestle a human [1]. As a result of this challenge, a few arm-wrestling robots were built using electroactive polymers (EAPs) [2]. The primary object of these arm-wrestling robots is to demonstrate the potential of EAP technology. These robots, however, do not have a broad range of functions related to arm-wrestling skills. Another effort relating to a humanoid robot arm has been in the field of prosthetic devices, such as the Utah Artificial Arm [3]. However, it does not appear that prosthetic devices are suitable for arm wrestling, in which strong arm force is required.

Several practical arm-wrestling devices have been patented as amusement units or as units for developing and strengthening wrist and arm muscles [4]–[7]. These devices are classified roughly into three types according to...