Design, Development, and Mobility test of an Omnidirectional Mobile Robot for Rough Terrain

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Abstract Omnidirectional vehicles have been developed and widely applied in several areas, but most of them are designed for the case of motion on flat, smooth terrain, and are not feasible for outdoor usage. This paper presents an omnidirectional mobile robot that possesses high mobility in rough terrain. The omnidirectional robot employs four sets of modules called active split offset caster (ASOC). The ASOC module has two independently-driven wheels that produce arbitrary planar translational velocity, enabling the robot to achieve its omnidirectional mobility. Each module is connected to the main body of the robot via a parallel link with shock absorbers, allowing the robot to conform to uneven terrain. In this paper, a design and development for the ASOC-driven omnidirectional mobile robot in rough terrain are described. Also, a control scheme that takes into account a kinematics of the omnidirectional mobile robot is presented. The omnidirectional mobility of the robot regardless of ifs heading direction is experimentally evaluated based on a metric called omnidirectional mobility index.

1 Introduction

An omnidirectional vehicle is capable of moving in any arbitrary direction and performing complex maneuvers that cannot be achieved by typical Ackermann steered wheeled vehicles. Omnidirectional vehicles have been investigated [1–3] and widely applied in many practical areas, such as mobile robotic bases for research, materials handling vehicles for logistics, and wheelchairs. Most omnidirectional vehicles to date have been designed to move on flat, smooth surfaces, employing specialized wheel designs [4–10], such as roller, Mecanum, or spherical

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14. ABSTRACT
Omnidirectional vehicles have been developed and widely applied in several areas, but most of them are designed for the case of motion on flat, smooth terrain, and are not feasible for outdoor usage. This paper presents an omnidirec-tional mobile robot that possesses high mobility in rough terrain. The omnidirec-tional robot employs four sets of modules called active split offset caster (ASOC). The ASOC module has two independently-driven wheels that produce arbitrary planar translational velocity, enabling the robot to achieve its omnidirectional mo-bility. Each module is connected to the main body of the robot via a parallel link with shock absorbers, allowing the robot to conform to uneven terrain. In this pa-per, a design and development for the ASOC-driven omnidirectional mobile robot in rough terrain are described. Also, a control scheme that takes into account a kinematics of the omnidirectional mobile robot is presented. The omnidirectional mobility of the robot regardless of ifs heading direction is experimentally evaluat-ed based on a metric called omnidirectional mobility index.

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wheels (Fig. 1). These wheels, however, are not practical for the use in outdoor because of the following reasons: small rollers may easily be clogged with debris or dirt. They also have a constraint on wheel diameter and width relative to the small slender rollers, and thus they cannot tolerate with large loads or cannot produce enough thrust power.

This paper introduces an omnidirectional mobile robot in rough terrain driven by active split offset caster (ASOC), which was initially proposed in [11] for indoor usage. The ASOC module employs two conventional wheels (i.e. pneumatic tire with rigid rim) with freely rotatable axes around pivot and roll. This ASOC module is integrated with suspension mechanism with parallel links to the main body of the robot, enabling an agile traversability on uneven terrain (Fig. 2).

In this paper, design and development for the ASOC-driven omnidirectional mobile robot for rough terrain are described. A kinematic control scheme that can coordinate each ASOC module (i.e. wheel velocity) to achieve a desired maneuver of the omnidirectional mobile robot is also presented. Experimental tests with different configurations of the robot have been performed to evaluate the omnidirectional mobility of the robot regardless of ifs heading direction

This paper is organized as follows: Section 2 introduces the detail design of the ASOC module and the system overview of the ASOC-driven omnidirectional mobile robot. Section 3 describes the kinematic control of the robot. The experimental test for the mobility evaluation of the robot is presented in Section 4

Fig. 1 Examples of roller wheels [9] and Mecanumm wheels [10]

Fig. 2 ASOC-driven omnidirectional mobile robot (left) and ASOC module (right)

2 ASOC-driven Omnidirectional Mobile Robot

2.1 Active Split Offset Caster: ASOC

Fig. 3 shows the ASOC module developed in this work. The assembly consists of a split wheel pair, a connecting axle, and offset link connecting wheel pair. The wheel pair/axle assembly freely rotates 360 degrees around the pivot axis. Another freely rotatable axis around roll is located at the middle of the wheel pair with an offset distance. The roll axis works to let the wheel pair maintain its contact on sloped or bumpy terrain surfaces. The angle of rotation of pivot and roll axes can be measured by the potentiometers.

The ASOC module can produce arbitrary (planar) translational velocities at a point along its pivot axis, by independently controlling each wheel's velocity. Two or more ASOC modules attached to a rigid robot body can thus produce arbitrary translational and rotational robot velocities. A control scheme is introduced in Section 3.

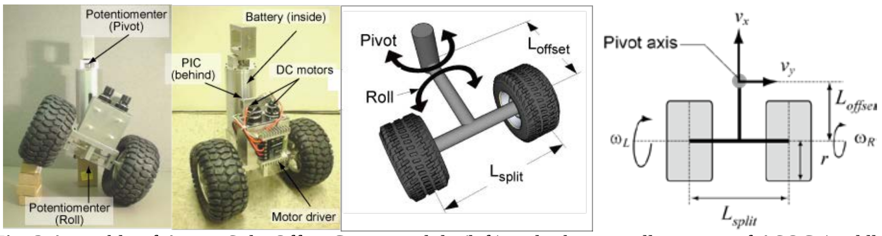


Fig. 3 Assembly of Active Split Offset Caster module (left) and schematic illustration of ASOC (middle and right)

2.1.1 Kinematic Isotropy for ASOC Design

All omnidirectional mobile robots are able to instantaneously travel in any planar direction. However, while some omnidirectional mobile robots exhibit preferred directions of travel, others exhibit equal mobility characteristics in all directions, i.e. "isotropic mobility." Hence, a kinematics isotropy is used to quantify the system's omnidirectional mobility.

Kinematic isotropy is defined as the condition in which a robot possesses a constant input velocity/output velocity ratio for all possible output velocity directions [12]. An isotropy metric is a measure of how close a robot is to the isotropy condition, and increases from 0.0 for a singular configuration (i.e. purely anisotropic, or non-omnidirectional) to 1.0 for kinematic isotropy. Ideally, an omnidirectional robot should possess a metric value of 1.0 for all joint space configurations, and thus not have a preferred direction of travel.

The kinematic parameters of the ASOC module such as L_{offset}, L_{split}, and wheel radius were selected to evaluate the effect of the parameters on the isotropy. As illustrated in Fig. 3, the Jacobian between wheel angular velocities (ω_R and ω_L) and translational velocity of ASOC module is given as follows:

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = r \begin{bmatrix} 1/2 & 1/2 \\ L_{offset}/L_{split} & L_{offset}/L_{split} \end{bmatrix} \begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix} \quad (1)$$

where v_x and v_y are the longitudinal and lateral translational velocities of ASOC axis, respectively. From the above equation, the wheel radius can be neglected for calculating the ratio of the eigenvalues, and therefore, the module isotropy is independent of the wheel radius.

Fig.4 shows an isotropy values over a range of L_{split}/L_{offset}. It can be seen that the isotropy depends on both L_{offset} and L_{split} and has a maximum value when L_{split}/L_{offset} ratio is equal to 2.0. This insight is useful for omnidirectional robot design, and then, the ASOC module has been designed to nearly achieve this value: L_{split}/L_{offset} ratio is 2.07, (L_{split} = 0.228 m, and L_{offset} = 0.110 m).

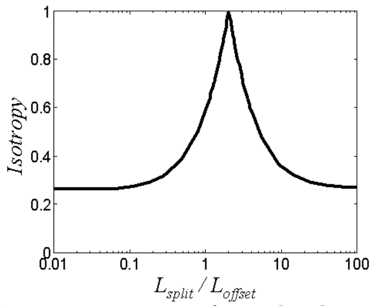


Fig. 4 Average isotropy for a robot driven by ASOC modules as a function of L_{split} / L_{offset} (from [13])

2.1.2 ASOC Components

The ASOC is a self-sustained “robotic” module, comprised of a power supply, two actuators, a microcontroller, a wireless device (Xbee), and a motor driver. Each module performs simple tasks assigned by the supervisory computer of the robot as well as executes local feedback control for wheel angular velocity.

Two actuators (MAXOS RE35) with planetary gear heads are located vertically between the wheels (see Fig. 3), each of which is connected to the left/right wheel via bevel gear. The wheel angular velocity is measured by a tachometer mounted on the tip of actuator. The maximum speed that ASOC module can produce is about 2.2 m/s (8.0 km/h). An off-the-shelf rubber coated wheel is used; the wheel radius is 85 mm and width is 86 mm. A local feedback control of wheel angular velocity is executed by a microcontroller, PIC18F4431 (40MHz).

The angle of rotations around the pivot and roll are measured by potentiometers on their axes. The data measured are handled by the microcontroller and sent to a supervisory computer mounted on the robot body via Xbee wireless communication device.

Power for the module is supplied by a serially connected 6 cells of Li-Ion batteries (3.2 Ah). The total weight of the module is 5.6 kg.

2.2 System Overview of Omnidirectional Mobile Robot

The omnidirectional mobile robot developed in this work consists of a main body and four ASOC modules. The ASOC modules, which are evenly spaced with 90 degrees intervals one another, are connected to the main body via parallel links with shock absorbers (Fig. 5). The suspension mechanism allows the robot to operate on rough terrain with moderate terrain adaptability.

A schematic diagram of the omnidirectional mobile robot is shown in Fig. 5. The onboard computer, Gumstix Overo Earth (600 MHz) running Linux, is mounted on the main body, working as a central computing devise. The onboard computer supervises all ASOC modules via Xbee wireless links such that the onboard computer kinematically coordinates ASOC modules to move the robot in a desired direction. GPS data is collected as ground truth data for outdoor experiments. These data are sent to an operator via IEEE 802.11g, along with ASOC motion data (i.e. potentiometer for pivot angle and wheel tachometer data).

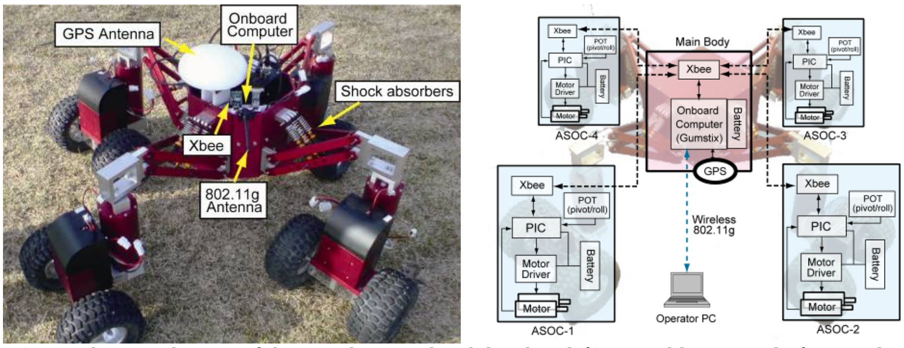


Fig. 5 Schematic diagram of the omnidirectional mobile robot (left). Dotted lines in right figure indicate wireless communication between them.

To avoid the interference between neighboring ASOCs, the distance *D* between the centroid of the main body and the ASOC pivot axis must be more than the square root of two times of the ASOC module workspace, $r_{workspace}$ (Fig. 6). This radius is the distance from the pivot axis to the most distal point of the wheel. Therefore, the geometric constrains of the robot configuration is as follows:

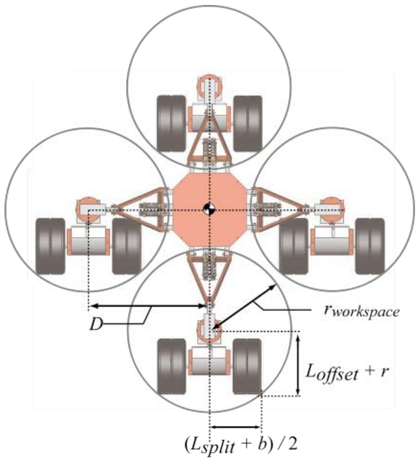


Fig.6 ASOC module workspace**.** The circles represent the boundaries of the workspace

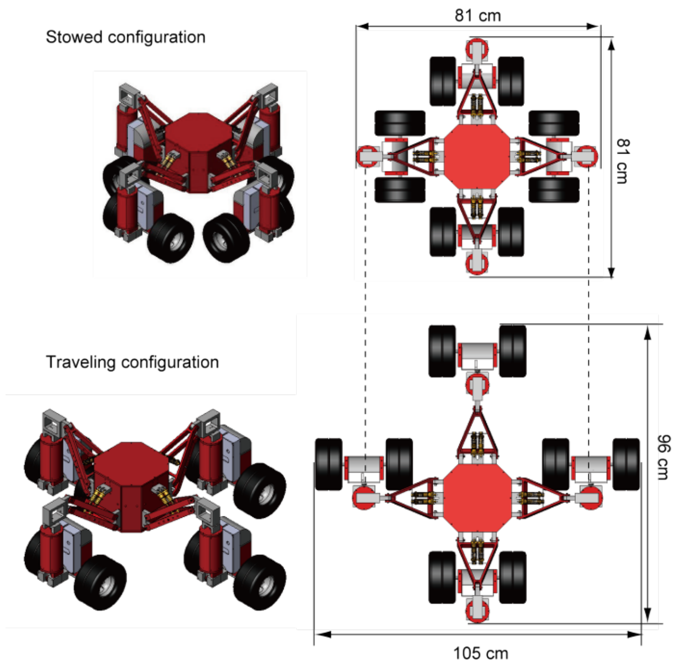


Fig.7 CAD model of the ASOC-driven omnidirectional mobile robot. Top figures show the robot in stowed configuration, and bottom ones show a traveling configuration.

$$D > \sqrt{2} r_{workspace} = \sqrt{2(L_{offset} + r)^2 + (L_{split} + b)^2 / 2} \tag{2}$$

where b is the wheel width. The distance D can be regulated by the length of the parallel links and stiffness of the shock absorbers. The geometric constraint in the above equation determined the dimension of the robot: 105 x 96 x 39 cm in its traveling configuration and 81 x 81 x 39 cm in its stowed configuration (Fig. 7). The weight is about 35 kg.

3 Kinematic Control of the Omnidirectional Mobile robot

Fig.8 illustrates a kinematic model of the ASOC-driven omnidirectional mobile robot. The coordinate frame for the main body Σ_b is fixed on the centroid of the body and defined as the right-hand frame, depicting the longitudinal direction as x. The coordinate frame for each ASOC module Σ_i (i=1…4) is defined such that the z axis is aligned to the pivot shaft and fixed at a point along its pivot axis (Σ_i does not rotate along with the ASOC rotation around its pivot axis). D and ξ_i locate each ASOC module with regard to the main body. Table 1 summarizes kinematic parameters that are used in the experiments described later.

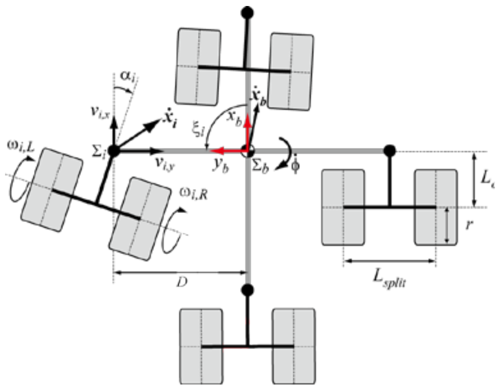


Fig. 8 Kinematic model of the ASOC-driven omnidirectional mobile robot.

Table 1 Kinematic parameters for the omnidirectional mobile robot

Symbol	Value
D	0.353 m
L_{offset}	0.110 m
L_{split}	0.228 m
r	0.085 m
ξ	[0, 0.5π, π, 1.5π]

The kinematic control explained here calculates all wheel angular velocities that satisfy desired body translational and rotational velocities defined in an inertial coordinate frame. First, the velocity of the ASOC module can be calculated as:

$$\dot{\boldsymbol{x}}_i = \begin{bmatrix} v_{i,x} \\ v_{i,y} \end{bmatrix} = \dot{\boldsymbol{x}}_b + \dot{\phi} D \begin{bmatrix} \cos\xi_i \\ \sin\xi_i \end{bmatrix} \quad (i = 1...4) \tag{3}$$

where, $\dot{\boldsymbol{x}}_i$ and $\dot{\boldsymbol{x}}_b$ are the planer velocity vectors at the i-th ASOC coordinate frame Σ_i and body frame Σ_b, respectively. $\dot{\phi}$ is the yaw rate of the main body. For kinematic control, $\dot{\boldsymbol{x}}_b$ and $\dot{\phi}$ are the input variables given by an operator. Note that the distance D is assumed as constant value in the experiment because the shock absorbers installed are relatively stiff enough so that the displacement of D is negligible.

The wheel angular velocities, $\omega_{i,L}$ and $\omega_{i,R}$, that yield the desired i-th ASOC velocity are formulated as follows:

$$[\omega_{i,L} \quad \omega_{i,R}]^T = \boldsymbol{C}^{-1} \dot{\boldsymbol{x}}_i / r \tag{4}$$

$\boldsymbol{C}$ is the coordinate transformation matrix, written as:

$$\boldsymbol{C} = \frac{1}{2} \begin{bmatrix} \cos\alpha_i + 2L\sin\alpha_i & \cos\alpha_i - 2L\sin\alpha_i \\ \sin\alpha_i - 2L\cos\alpha_i & \sin\alpha_i + 2L\cos\alpha_i \end{bmatrix} \tag{5}$$

where, α_i is the angle of the pivot axis, measured by the potentiometer, and $L = L_{offset} / L_{split}$. The wheel angular velocity obtained from the above equations is then achieved via simple PID feedback control.

Note that the control method described above aligns the thrust vector of each ASOC in the desired direction of travel, minimizing energy loss due to internal forces.

4 Experimental Tests for Omnidirectional Mobility

In this section, first, a metric defined as an omnidirectional mobility index is introduces to evaluate the mobility of the robot in different configuration and maneuvers. Then, the experimental results are summarized along with the mobility evaluation.

4.1 Omnidirectional Mobility Index

Several metrics have been studied for the mobility analysis of mobile vehicles in rough terrain. For example, a mobility index for off-road vehicle based on factors such as contact pressure and weight was proposed in [14]. Also, a tractive efficiency (ratio of input and output powers) of vehicle has been employed to compare performance of off-road vehicles. These indexes basically consider a dynamic interaction between vehicle and terrain. Another metric with a body motion (i.e. velocity, acceleration, or jerk) is commonly used to evaluate the mobility of conventional passenger vehicles or mobile robots.

Focusing on the mobility of omnidirectional vehicle, a particular requirement is high agility for a near-arbitrary omnidirectional maneuver. In the case of an ASOC-driven omnidirectional mobile robot, each ASOC needs to be kinematically coordinated to achieve a given maneuver. Therefore, in this work, a metric related to the ASOC motion is employed for mobility evaluation. The metric, termed an omnidirectional mobility index, is defined as a root mean square error (Fig .9) between the desired profile of the ASOC pivot angle and its actual profile measured by potentiometer on its axis. The index has a unit of degrees. The smaller the magnitude of the index, the more agile the omnidirectional vehicle. In the experiment, a net omnidirectional mobility index of an assigned maneuver is calculated as a mean value between the indexes obtained from four ASOCs.

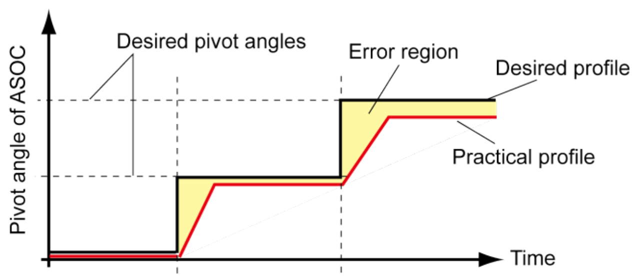


Fig.9 Schematic graph for a time history of pivot angle of ASOC. The black line is the desired profile (given maneuver) and the red line is the measured profile (actual maneuver). The yellow region indicates error between desired and measured pivot angle.

4.2 Experimental Description

Two different configurations have been experimentally tested as shown in Fig. 10: in Configuration 1, the velocity vector of the robot is always aligned with the ASOC module orientation (i.e. a cross-shape configuration); in Configuration 2, the velocity vector is diagonal (45 degrees) with regard to the ASOC module orientation (i.e. X-shape configuration).

In the experimental test, the robot changes its velocity vector by 90 degrees in every 5 seconds, drawing a square motion path. The traveling velocity of the robot is controlled to maintain a constant value of 0.36 m/s. Each ASOC module calculates wheel angular velocity required for the maneuver based on the kinematic control method as presented in Section 3. During each run, the pivot angle and wheel velocity at each ASOC are measured and sent to the onboard computer for post-analysis of mobility evaluation.

The effect of suspension design on omnidirectional mobility is examined by comparing the results from the robot with a standard, compliant suspension (parallel links with the shock absorbers) to results from the robot with a suspension composed of rigid links.

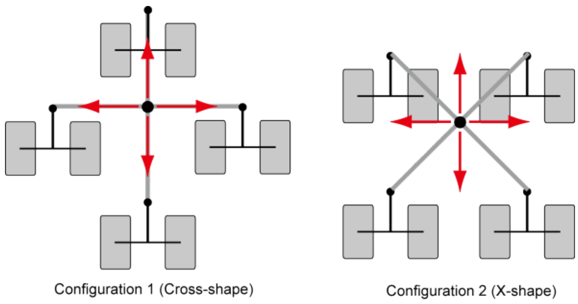
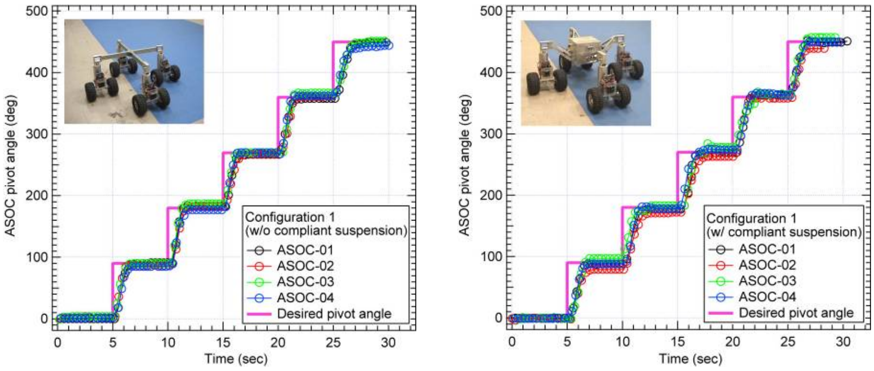


Fig. 10 Two configurations tested in the experiment. The red arrows indicate the velocity vector of the desired maneuver

4.3 Results and Discussion

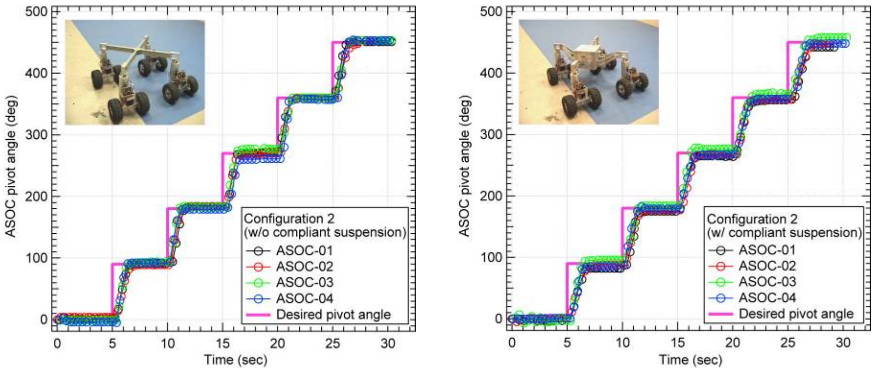
Fig. 11 and Fig. 12 show a time history of the pivot angle in different configurations with and without compliant suspension, respectively. Also, the omnidirectional mobility index for each configuration is summarized in Table 2.

From the figures and table, the omnidirectional mobility indices between the two configurations is negligible: it is less than 0.1 degrees in the case of the robot without the compliant suspension, and 1.6 degrees with. This indicates that the ASOC-driven omnidirectional robot possesses relatively high agility that is independent of its configuration.



(a) w/o compliant suspension (b) w/ compliant suspension

Fig. 11 Time history of the pivot angle for mobility evaluation (Configuration 1).



(a) w/o compliant suspension (b) w/ compliant suspension

Fig. 12 Time history of the pivot angle for mobility evaluation (Configuration 2).

Table 2 Omnidirectional mobility index at each configuration with and without compliant suspensions (Unit is degrees).

	Configuration 1		Configuration 2	
	w/o compliant suspension	w/ compliant suspension	w/o compliant suspension	w/ compliant suspension
ASOC 0	31.67	34.19	29.61	34.39
ASOC 1	29.68	37.05	30.95	35.77
ASOC 2	27.83	29.46	28.19	27.51
ASOC 3	30.46	33.02	30.60	29.62
Mean	29.91	33.43	29.84	31.82

In addition, it can be seen that the omnidirectional mobility of the robot with rigid links (without compliant suspension) is better than the robot with compliant suspension. This is due to the fact that the shock absorbers for the compliant suspension mitigate sudden velocity change. The shocks absorbers also reduce thrust energy generated at the wheel contact patch while turning, resulting in a less agile turning maneuver.

On the other hand, the robot with the rigid links can efficiently coordinate each ASOC with less energy loss, enabling more agile maneuver. This result indicates that a trade-off between a high terrain adaptability with compliant suspension and high omnidirectional mobility with rigid links is necessary.

5 Conclusions

This paper has presented a design and development of the ASOC-driven omnidirectional mobile robot. The system overview of the robot has been described, along with the kinematic isotropy analysis for ASOC design as well as the geometric constraints of the robot, that have been used for the practical design of the robot. Also, the kinematic control method of the robot which coordinates each ASOC motion has been addressed.

The mobility of the omnidirectional mobile robot with different configurations has been experimentally evaluated based on the omnidirectional mobility index. The experimental evaluations confirm that the robot has an ability to move in any directions regardless of its configuration. Also, the result implies that an optimization of the suspension properties (i.e. length, stiffness) will be necessary to satisfy better terrain adaptation as well as high agility of omnidirectional motion.

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