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Design of Omnidirectional Mobile Robots with ACROBAT Wheel Mechanisms

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Abstract—**In this paper, we study the design of omnidirectional mobile robots with Active-Caster RObotic drive with BAll Transmission (ACROBAT). ACROBAT system has been developed by the authors group which realizes mechanical coordination of wheel and steering motions for creating caster behaviors without computer calculations. A motion in the specific direction relative to a robot body is fully depends on the motion of a specific motor. This feature gives a robot designer to build an omnidirectional mobile robot propelled by active-casters with no redundant actuation with a simple control. A controller of the robot becomes as simple as that for omni-wheeled robotic bases. Namely 3DOF of the omnidirectional robot is controlled by three motors using a simple and constant kinematics.**

ACROBAT includes a unique dual-ball transmission to transmit traction power to rotate and orient a drive wheel with distributing velocity components to wheel and steering axes in an appropriate ratio. Therefore a sensor for measuring a wheel orientation and calculations for velocity distributions are totally removed from a conventional control system. To build an omnidirectional vehicle by ACROBAT, the significant feature is some multiple drive shafts can be driven by a common motor which realizes non-redundant actuation of the robotic platform.

A kinematic model of the proposed robot with ACROBAT is analyzed and a mechanical condition for realizing a non-redundant actuation is derived. Based on the kinematic model and the mechanical condition, computer simulations of the mechanism are performed. A prototype two-wheeled robot with two ACROBATs is designed and built to verify the availability of the proposed system. In the experiments, the prototype robot shows successful omnidirectional motions with a simple and constant kinematics based control.

I. Introduction

The holonomic and omnidirectional mobile capability gives many advantages on the wheeled mobile platforms. Flexible and high maneuverable motion planning can be realized by motion planners of mobile robots since it is not needed to take into account non-holonomic constraints. Additionally, the omnidirectional mobility is also very friendly for human operators since they do not have to understand the principle of a drive mechanism and its configuration at all. A human driver only commands the direction and magnitude of the desired motion since a holonomic and omnidirectional mechanism can start to move in arbitrary direction with an arbitrary mechanical configuration such as an orientation of a wheel.

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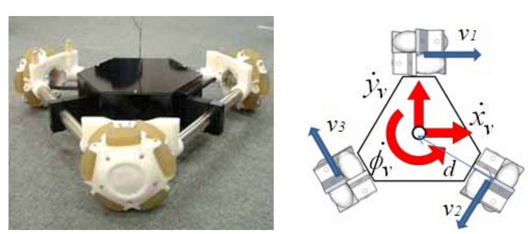
In the past, lots of omnidirectional drive mechanisms have been developed, such as Universal-wheel[1](Fig.1), Mechanum-wheel[2], Orthogonal ball wheel unit[3], Vuton crawler[4], Ball-wheel[5], etc. Basically this class of wheel mechanisms provides an active traction force in a specific direction while it can be passively moving in the direction perpendicular to the active direction because of free rolling mechanisms.

These omnidirectional vehicles are controlled by simple and constant robot kinematics whose example is shown in eq(1). By using this constant kinematics, robots can be driven by a simple control architecture as shown in Fig.2. Thus step motors with no feedback or chap DC motors with local speed feedback can be used to create 3DOF motions of the conventional omnidirectional mechanisms.

This simple control structure is acceptable for many robot researchers and students therefore this configuration is widely used on mobile bases such as those for soccer robot competitions, service robots, wheelchair robots, etc.

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & d \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & d \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & d \end{bmatrix} \begin{bmatrix} \dot{x}_v \\ \dot{y}_v \\ \dot{\phi}_v \end{bmatrix} \tag{1}$$



(a) Overview (b) 3DOF of the robot

Figure 1 :Omnidirectional robot with three omni-wheels

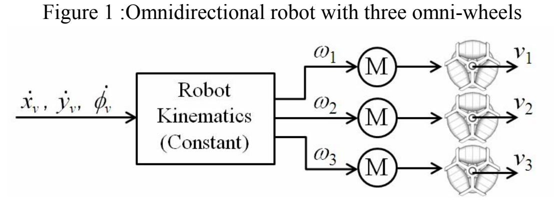


Figure 2 :Control system of a three-wheeled omnidirectional robot

All of the omnidirectional systems mentioned above are good for laboratory uses. However, these require special kind of wheels, such as large wheels with many free barrel shaped rollers, spherical wheels, etc. These may include difficulties in practical applications in which rubber or pneumatic tires are required for reducing vibrations or for enhancing ground contacts between the wheels and the ground. Usually these mechanisms do not present enough step climbing capabilities because of the small radius of the free rollers or small clearance between the ground and the bottom of robotic platforms.

To overcome these difficulties on the conventional omni-wheels, an active-caster system [7]-[11], which we call as ACRO in this paper, was proposed. The ACRO is a different class of omnidirectional mechanism which provides active traction force in an arbitrary direction, namely it has the active 2DOF mobile capability on the ground with no free rolling mechanisms nor spherical wheels.

The ACRO[7] has two actuators to control wheel rotation and steering rotation independently to create 2DOF planar motion. To achieve the omnidirectional motion of ACRO, precise coordination between the two actuators are required to avoid confliction of motions, because at least four actuators are needed to design a robotic platform moving the planar surface with 3DOF, namely it has redundancy in the actuation.

In this paper, an omnidirectional robot with ACROBAT is proposed which includes a novel dual-ball transmission for avoiding the problem of the redundant actuation and the complicated coordination control. In the following sections, kinematics of ACROBAT system and design conditions of omnidirectional robot with ACROBATs are analyzed, followed by simulations, the prototype robot design. Some fundamental experiments using the prototype robotic base are performed to verify the proposed omnidirectional system.

II. ORIGINAL ACTIVE-CASTER MECHANISM(ACRO)

A. Kinematics

Figure 3 shows a top view of an original active-caster[8], ACRO. This mechanism equips a drive wheel which is off-centered from a center of the steering axis. ACRO equips with two motors for actuating the wheel shaft for $\dot{x}_w$ control and the steering shaft for $\dot{y}_w$ control (these velocity vectors are shown in Fig.3). These component vectors have to be precisely controlled for correct coordination not to conflict to other motor movements. To derive the required shaft rotation, kinematics of the wheel mechanism, eq.(2) is used.

$$\begin{bmatrix}\omega_w\\ \omega_s\end{bmatrix}=\begin{bmatrix}\dfrac{1}{r} & 0\\ 0 & \dfrac{1}{s}\end{bmatrix}\begin{bmatrix}\dot{x}_w\\ \dot{y}_w\end{bmatrix}=\begin{bmatrix}\dfrac{\cos\phi}{r} & \dfrac{\sin\phi}{r}\\ -\dfrac{\sin\phi}{s} & \dfrac{\cos\phi}{s}\end{bmatrix}\begin{bmatrix}V_x\\ V_y\end{bmatrix} \qquad (2)$$

Note that V_x and V_y are the components of the commanded velocity **V** along x- and y-axis of the robot body coordinate system. This equation represents the ACRO kinematics used for the wheel and steering motor coordinated control based on the orientation of the wheel ϕ.

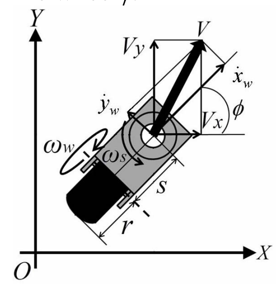


Figure 3. Velocity control of an active-caster [7]

B. Two-wheeled Robotic Base

Figure 4 shows a schematic overview of an omnidirectional mobile robot with two ACROs. The robot with a pair of ACROs is controlled by four motors which involves one redundant DOF in actuation. To coordinate the multiple drive wheels, motors on ACRO are controlled based on the velocity based robot inverse kinematics which is represented as eq.(3).

The coordination control of actuators using (2) and (3) enables each active-caster to emulate “caster motion” which can be seen on the bottom of the shopping carts, conference tables and chairs. The control system of a robot with ACROs is shown in Fig.5. Thus ACRO system realizes the omnidirectional motion with no free rolling mechanical parts however it includes some problems 1) the redundant actuation: a robot base needs at least four motors to control 3DOF of the platform, 2) the precise motion control: computer calculations and accurate servos for velocity distribution.

$$\begin{bmatrix}\dot{x}_1\\ \dot{y}_1\\ \dot{x}_2\\ \dot{y}_2\end{bmatrix}=\begin{bmatrix}1 & 0 & -W/2\\ 0 & 1 & 0\\ 1 & 0 & W/2\\ 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\dot{x}_v\\ \dot{y}_v\\ \dot{\phi}_v\end{bmatrix} \qquad (3)$$

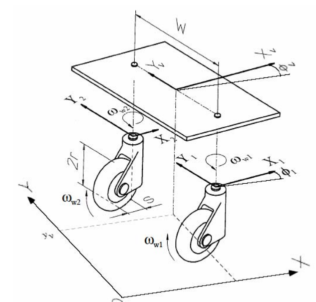


Figure 4. Overview of an omnidirectional robot with ACROs

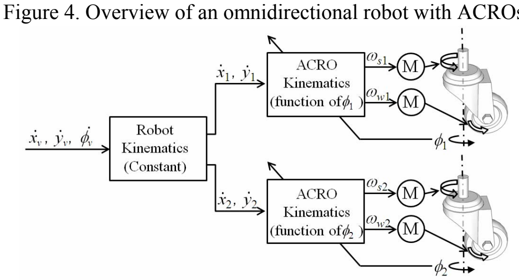


Figure 5. Control architecture of omnidirectional robot with ACROs

III. DUAL-BALL TRANSMISSION ON ACROBAT

A. Configuration of ACROBAT

To overcome the problems on the ACRO system, we have proposed a new active-caster mechanism which includes a dual-ball transmission, we call this mechanism as ACROBAT(Active-Caster RObotic drive with BAll Transmission)[12].

A dual-ball transmission is introduced for realizing velocity distribution which represented in eq.(2) by a mechanical movement not by a coordinated motor control. For the purpose, we design a mechanism to decompose a velocity vector into two components for wheel and steering drives.

Figure 6 shows a schematic overview of ACROBAT. Two balls are located in the mid part of a drive train between actuators and the wheel.

The proposed transmission design includes two balls which is similar to a robotic platform with ball wheels. In contrast to the conventional ball wheel robots, balls in ACROBAT do not touch to the ground directly and contact pressures between two balls can be controlled to maintain an appropriate value. Therefore, we can specify the transmittable traction power in the design process.

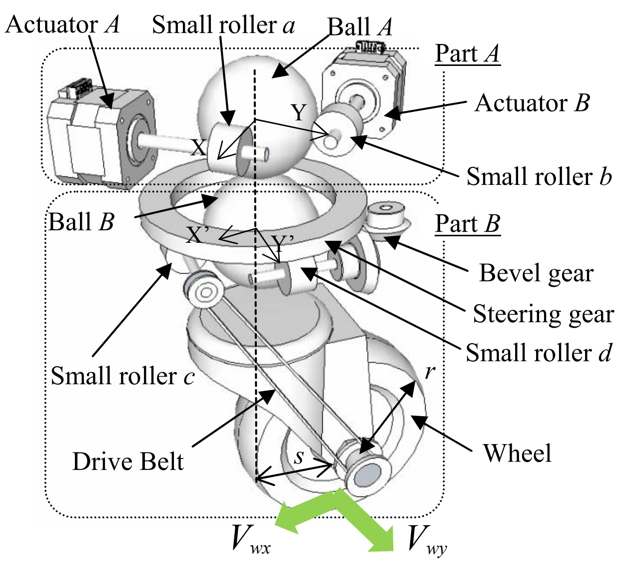


Figure 6 The configuration of ACROBAT

ACROBAT is composed of two parts, *A* and *B*. The part *A* includes a large ball *A* and two actuators for drive the ball *A* via small rollers contacting to the ball *A*. As the small rollers rotate about the horizontal axes, the ball *A* rotates about a horizontal axis while its rotation about the vertical axis is restricted.

The part *B* includes another large ball *B* whose traction force is distributed to another pair of small rollers. One of the rollers is connected to a wheel axis the other is connected to a steering axis for driving these axes. The ball *A* and *B* make point contact to transmit traction forces from part *A* to part *B*, as shown in Fig.7. In normal designs, part *A* might be fixed to a robot body. The part *B* can be rotated about the vertical axis since part *A* and part *B* is connected by a ball bearing.

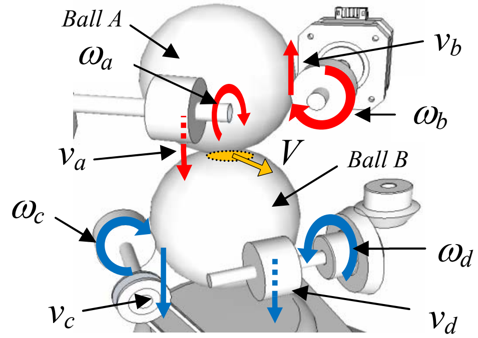


Figure 7 A dual-ball transmission

B. Kinematics of ball-roller drive system

Now, we consider the kinematics of a fundamental ball-roller drive system. Figure 8 shows the top and side views of the ball-roller system in which the coordinate frame is attached to locate its origin at the center of the ball and the XY plane lies horizontally. The roller *a* and *b* contact with the ball surface at angles α and β from X axis respectively. Since the axes of the rollers are along the horizontal direction, the ball rotation about the vertical axis is restricted by the rollers. As the rollers rotate in ω_a and ω_b simultaneously, the ball rotates in angler velocity Ω_s about a horizontal axis which directs θ_s from the X axis. Then following equations can be derived.

$$
\begin{aligned}
R_a &= R_s \sin(\theta_s - \alpha) \\
R_b &= R_s \sin(\theta_s - \beta)
\end{aligned}
\tag{4}
$$

where R_s is a radius of the ball while R_a and R_b are the radius of the contact circles, those are contact point trajectories of the roller *a* and *b* on the ball surface. We define a circumferential velocity V_i at the bottom point of the ball which is represented as,

$$
\begin{aligned}
V_i &= R_s \Omega_s \\
v_a &= R_a \Omega_s \\
v_b &= R_b \Omega_s
\end{aligned}
\tag{5}
$$

where v_a and v_b are the respective contact point velocities between the ball and the rollers. From eq.(4) and (5), we get

$$
\begin{aligned}
v_a &= V_x \cos\alpha + V_y \sin\alpha \\
v_b &= V_x \cos\beta + V_y \sin\beta
\end{aligned}
\tag{6}
$$

V_x and V_y are the velocity components of the circumferential velocity V_i along the X-axis and Y-axis respectively.

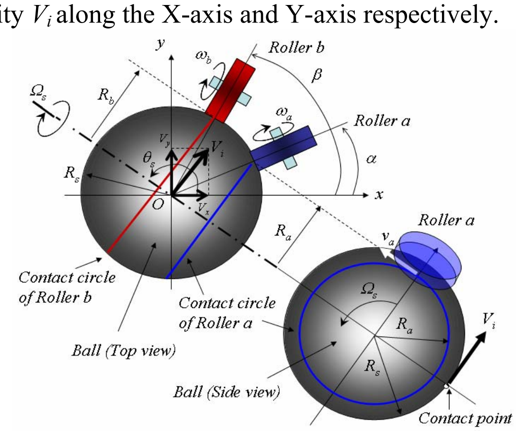


Figure 8 A ball contacting with two rollers

Now we get ball-roller kinematics which represents the relationships between ω_a, ω_b and V_x, V_y as,

$$\begin{bmatrix}\omega_a\\ \omega_b\end{bmatrix}=\begin{bmatrix}\dfrac{\cos\alpha}{r_a} & \dfrac{\sin\alpha}{r_a}\\ \dfrac{\cos\beta}{r_b} & \dfrac{\sin\beta}{r_b}\end{bmatrix}\begin{bmatrix}V_x\\ V_y\end{bmatrix} \tag{7}$$

By inverting eq.(7), we derive

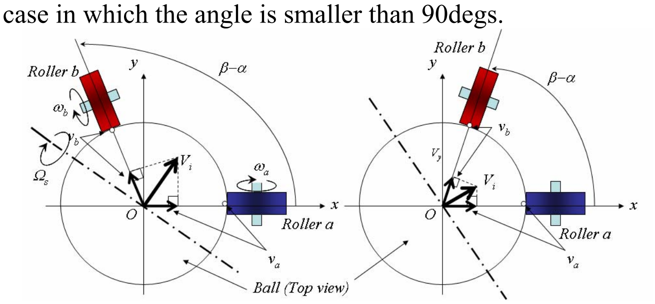
$$\begin{bmatrix}V_x\\ V_y\end{bmatrix}=\frac{1}{\sin(\alpha-\beta)}\begin{bmatrix}-r_a\sin\beta & r_b\sin\alpha\\ r_a\cos\beta & -r_b\cos\alpha\end{bmatrix}\begin{bmatrix}\omega_a\\ \omega_b\end{bmatrix} \tag{8}$$

Additionally following parameters can be calculated as,

$$\theta_s=\tan^{-1}\left(\frac{r_a\omega_a\sin\beta-r_b\omega_b\sin\alpha}{r_a\omega_a\cos\beta-r_b\omega_b\cos\alpha}\right) \tag{9}$$

$$\Omega_s=\frac{\sqrt{r_a^2\omega_a^2+r_b^2\omega_b^2-2r_a\omega_a r_b\omega_b\cos(\alpha-\beta)}}{-R_s\sin(\alpha-\beta)} \tag{10}$$

From eq.(8), we derive the circumferential velocity V_i at the bottom of the ball. Note that this V_i vector does not conform the ordinal graphical law, namely the parallelogram law. Fig. 9(a) and (b) show graphical relationships of V_i and v_a, v_b. Figure 9(a) shows that the two rollers contacting the ball with a relative angle greater than 90degs and (b) shows the other case in which the angle is smaller than 90degs.



(a) Case (β–α) > 90degs (b) Case (β–α) < 90degs

Figure 9 Vector sum on spherical surface

In Fig.9, the roller *a* and *b* rotate to provide contact velocities v_a and v_b on the ball surface. Let us define the X-axis to intersect with the contact point of roller *a*. Considering that the each contact velocity vector is translated to the bottom of the ball along the spherical surface, these vectors can be seen as arrows as shown in Fig.9. Usually, a resultant velocity vector can be derived from the parallelogram law in the normal vector sum method. However in this case, the resultant circumferential velocity V_i is graphically represented as Fig.9, namely the end point of the V_i is defined as an intersection of two perpendiculars at the endpoints of the component vectors, v_a and v_b.

Only if these rollers contact with the ball to be right angles to each other, the resultant vector would be identical to the result of the parallelogram law. When β-α=π/2, eq.(8) can be simplified as,

$$\begin{bmatrix}V_x\\ V_y\end{bmatrix}=\begin{bmatrix}r_a & 0\\ 0 & r_b\end{bmatrix}\begin{bmatrix}\omega_a\\ \omega_b\end{bmatrix} \tag{11}$$

In ACROBAT system, rollers in part *B* have to contact with the ball *B* to be right angles. The right angle configuration in part *B* realizes the appropriate velocity distribution which is represented by the ACRO kinematics, eq.(2).

When the rollers in part *A* contact with the ball *A* to be right angles as well, the overall kinematics of ACROBAT is represented as,

$$\begin{bmatrix}\dot{x}_a\\ \dot{y}_a\end{bmatrix}=\mathbf{R}\begin{bmatrix}\omega_{ax}\\ \omega_{ay}\end{bmatrix} \tag{12}$$

where

$$\mathbf{R}=\begin{bmatrix}p\cos^2\theta+q\sin^2\theta & -(p-q)\cos\theta\sin\theta\\ (p-q)\cos\theta\sin\theta & -p\sin^2\theta-q\cos^2\theta\end{bmatrix}$$

p and *q*: constants determined by the gear ratios in the drive trains and some mechanical parameters.

By choosing a mechanical condition of design parameters, *p*=*q* can be satisfied. Then eq.(12) is greatly simplified as,

$$\begin{bmatrix}\dot{x}_a\\ \dot{y}_a\end{bmatrix}=\begin{bmatrix}K_1 & 0\\ 0 & -K_2\end{bmatrix}\begin{bmatrix}\omega_{ax}\\ \omega_{ay}\end{bmatrix} \tag{13}$$

where K_1 and K_2 are constants. Details for deriving the eq(12) and (13) are presented in the reference [12].

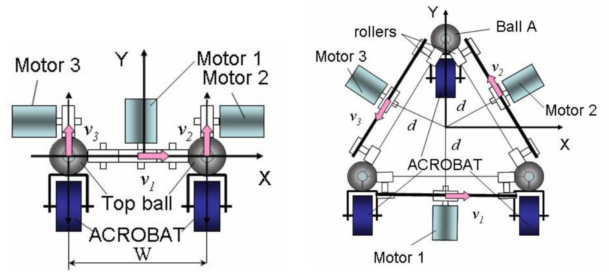
Thus ACROBAT kinematics is not a function of the wheel orientation θ, therefore the motions of ACROBAT can be controlled by calculating the constant kinematics, eq.(13). This feature simplifies a control system and a robot hardware, as mentioned in the introduction section.

C. Omnidirectional robot with ACROBATs

In the previous section, we derived a kinematic model of the ball-roller system. In general, rollers do not have to take right angle configurations in the part *A*. Depending on the number of motors and the layout of wheels on the robotic frame, the angle of the roller can be varied from the standard right angle configuration.

By the study in the previous section, it is clarified that a velocity component along a line, which connects the center of the ball and the contact point of the roller, would completely depend on the specified roller rotation but does not get any effects from the other roller location or a rotation speed at all. In Fig.9, the orientation and the magnitude of the resultant vector V_i are varied by the location of roller *b*(the angle β–α), the velocity component along the x-axis is maintained to be v_a at all times. Therefore some rollers in plurality of ACROBATs, that provide velocities along an identical direction to a robot body, can be driven by a common actuator. For instance, rollers "*a*" in Fig.9(a) and (b) give identical rotations, namely along x-axis, these rollers "a" can be driven by a common motor, although rollers "*b*" make contacts to the balls in different angles.

The fundamental solution to satisfy the conditions is a two-wheeled robot in which a pair of rollers are driven by a common motor and individual two motors drive the "*a*" balls from different directions as shown in Fig.10(a). By extend this idea, an omnidirectional robot with three-ACROBATs in which three pairs of rollers are driven by three common motors could be one of the possible configurations, whose schematic is shown in Fig.10(b). This triangle configuration can be considered as a combination of three pairs of common drive as shown in Fig.11. Note here that a triangle is not necessary to be an equilateral triangle.



(a) 2-wheel configuration (b) 3-wheel configuration

Figure 10 Possible omnidirectional robotic bases using ACROBATs

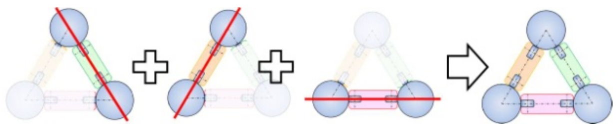


Figure11 Concept of 3-wheel robot (three pairs of a common drive unit)

The robot kinematics for the robot in Fig.10(a) is derived as,

$$\begin{bmatrix} \dot{x}_v \\ \dot{y}_v \\ \dot{\phi}_v \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & \frac{1}{W} & -\frac{1}{W} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} \tag{14}$$

And that for the robot in Fig.10(b) is also derived as,

$$\begin{bmatrix} \dot{x}_v \\ \dot{y}_v \\ \dot{\phi}_v \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\ \frac{1}{3d} & \frac{1}{3d} & \frac{1}{3d} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} \tag{15}$$

IV. Analysis of Actuation Index

One of the criteria of automated machines is *Actuator Index* which represents an actuator usage efficiency. The basic concept of the efficiency was proposed in [13] in which *Actuation Index* η_p is defined as,

$$\eta_p \equiv \frac{Possible\ \ Output\ \ Power}{Sum\ \ of\ \ Installed\ \ Actuators\ \ Power} \tag{16}$$

To maximize this *Actuation Index* is the one of the directions of robot designs to minimize the sum of the actuator power on a robot, which directly affects on the weight and the size of actuators. In[13], the design concept of "coupled actuation" or "coupled drive" was introduced which realizes a specific robot motion by actuating multiple actuators simultaneously. This is a type of parallel coupled drive to maximize the *Actuation Index*.

In this section, we investigate *Actuation Index* on the proposed omnidirectional robot with ACROBATs. Since this mechanism realizes not only a non-redundant drive but an efficient drive from the view point of *Actuation Index*.

Let us consider the two-wheeled omnidirectional robot shown in Fig.10(a).

Considering the robot motion along the x-axis, only motor 1 has to be actuated while motors 2, and 3 must stop during the specific motion. Therefore, power of motor 1 can contribute to the robot motion in X-direction. The maximum *Actuation Index* in the direction would be derived from,

$$\eta_{p(x-direction)} \equiv \frac{Rated\ \ Power\ \ of\ \ Motor\ \ 1}{\sum_{n=1}^{3}(Rated\ \ Motor\ \ Power)} \tag{17}$$

When the robot moves in the direction 45degs from the X-axis, the three motors have to drive the ball surface at the same speed that results in providing the translational velocity and traction force both of that are $\sqrt{2}$ times than the motion along X-axis. Therefore provided power becomes twice of that for the motion in X-direction which reaches 100% of the sum of equipped motor power. Thus *Actuation Index* of the translation motion of the 2-wheeled robot can be derived. Fig.12 shows *Actuation Index* in all directions. Here we suppose that the motor 1 has doubled capacity than the motors 2 or 3 since motor 1 drives two balls simultaneously.

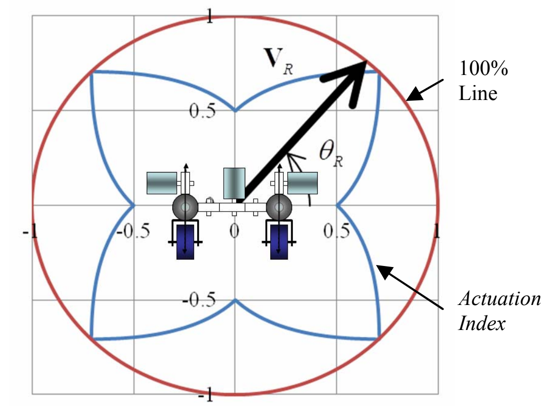


Figure12 Actuation Index for contact angles π/2

This Actuation Index profile can be varied by the contact angle of the independent rollers driven by the motors 2 and 3. If contact angles are set to 2/3π rads from x-axis as shown in the mid of Fig.13, a profile of *Actuation Index* becomes irregular and a line of symmetry appears in 1/3π rads.

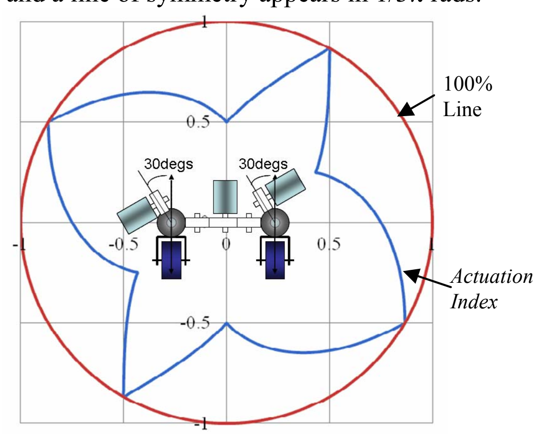


Figure13 Actuation Index for contact angles 2/3π

From the viewpoint of omnidirectional robot applications, asymmetricity of the mobile capability is not appropriate. Therefore we choose the 2-wheel configuration shown in Fig.12 for the prototype design where the front of the robot to be set at 45degs from the X-axis, namely two drive wheels are located at diagonal positions on a robot frame.

V. Robot Simulations

To verify the mobile capability of the proposed omnidirectional robot with ACROBATs, computer simulations are performed. Using robot kinematics derived in the previous section and wheel kinematics which details discussed in [12], a typical motion is analyzed. The robot is expected to show omnidirectional motion with “caster motion” in ACROBAT mechanism with no sensor nor coordinated motor control. To verify this performance, we test behaviors of the robot in which 3DOFs are simultaneously generated, namely translation motion in x and y directions and rotation of the robot body. Figure 14 shows one of the simulation results. The angles of drive wheels on ACROBATs are set 0deg at initial condition. The robot is commanded to move along a line with a constant rotation. The velocity reference in each DOF is $\dot{x}_v = 0.21 m/s$, $\dot{y}_v = 0.19 m/s$ and $\dot{\phi}_v = 0.5 rad/s$, respectively.

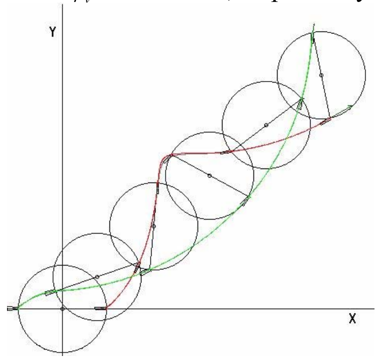


Figure 14 Simulation of an omnidirectional robot with two ACROBATs

VI. Prototyping

A. Prototype mechanism

To confirm the proposed mechanism working in the real world, we designed a prototype omnidirectional robot with two ACROBATs. Specifications of ACROBAT for the prototype design are shown in Table1. Figure 15 and 16 show a 3D design and an overview of the ACROBAT prototype. Two stainless steel balls for ball bearing use are used for the large balls in part *A* and *B*. In part *A*, small rollers are contact with the large ball at the right angle each of that is driven by an independent motor. The large ball is spring loaded horizontally to contact with both rollers firmly. Two spherical bearings are installed at the top of the upper ball and the bottom of the lower ball to support the dual-ball transmission. Another set of springs provides appropriate load between the balls along the vertical direction via the spherical bearing at the top. Two ACROBATs are mounted on an Aluminum plate which is a 0.6x0.6 square with 10mm thickness. The power of motor1(X-motor) is transmitted to two ACROBATs via a bevel gear and a drive belt as shown in Fig.17. ACROBATs are separated with a distance of 0.5m, each of the mechanism is located at the corner of the robot frame therefore the front side of the robot is 45degs from the x-axis of the ACROBAT coordinates. The overview of the prototype robot is shown in Fig.18.

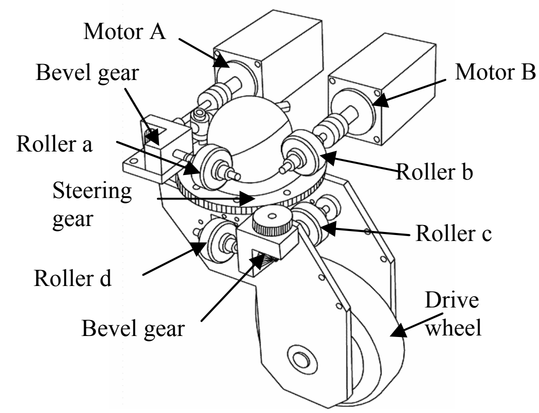


Figure 15 Prototype design of the active-caster

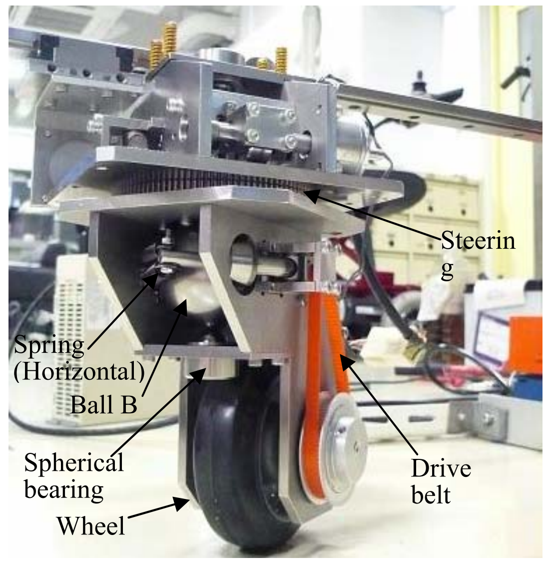


Figure 16. Overview of ACROBAT prototype

Table1. Specifications of prototype robot with ACROBATs

Radius of small rollers	r	12.5 mm
Gear ratio	G_t,	4 (roller to wheel)
	G_p	4 (roller to steering)
Wheel radius	R	50 mm
Caster offset	s	50 mm
Large ball diameter		50.8mm (2”)
Wheel distance	W	0.5 m
Robot frame dimension		0.6 x 0.6 m
Motor capacity		100W(motor1), 50W(motor2,3)

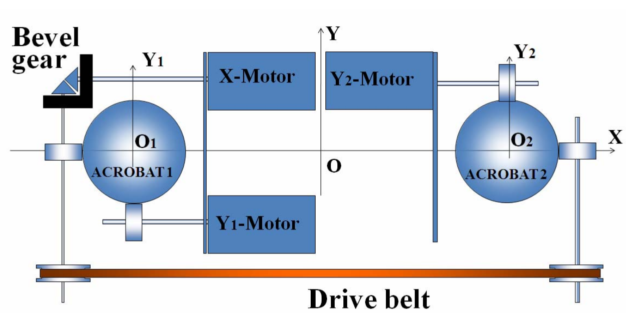
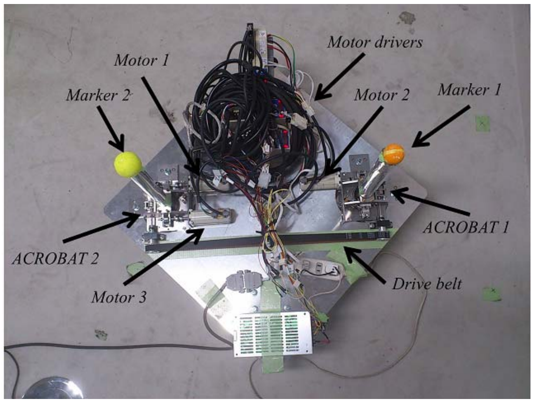
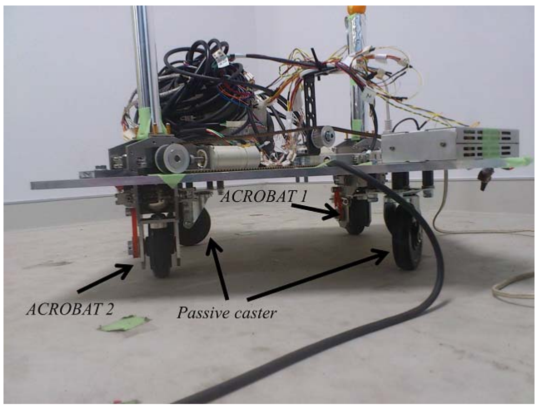


Figure 17 A Three-motor arrangement on the prototype robot



(a) Top view



(b) Side view

Figure 18 Holonomic omnidirectional mobile robot with two ACROBATs

B. *A Control system for prototype robot*

Since ACROBAT is able to coordinate wheel and steering motions by the ball transmission mechanism, the robot controller may just send velocity references to motors with using a simple robot kinematics, which structure is shown in Fig.19. This controller architecture is quite simple compared with controller designs for conventional ACRO robots which example is shown in Fig.5. Each motor is controlled by a simple velocity controller, which is often called as a motor driver or a motor amp by applying a appropriate voltage to a motor by a power circuit.

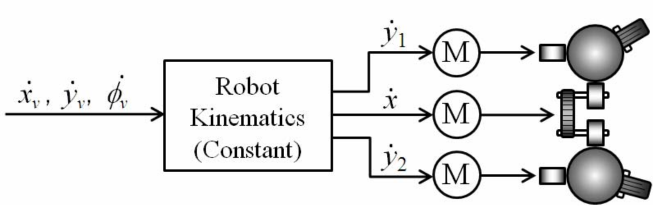


Figure 19 Control block diagram for the omnidirectional robot prototype

VII. Experiments

To test the omnidirectional mobility of the proposed system, fundamental motions are performed. Since rotations and orientations of drive wheels on ACROBATs can not be detected, we measure the robot motion by using a stereo camera positioning system. In Fig.18, it is seen that two markers are mounted on the top of the robot frame, which is used for the camera system. The robot motions are created by sending velocity commands to three motors with simple velocity control, the resultant robot motions are detected and recorded by the camera system.

Figure20(a)-(c) show one of the simplest experimental results. Figure20(a) shows translation motion of the robot along X-direction in which only motor 1 was commanded to rotate while the motors 2 and 3 were commanded to stop. In the figure, a line on the left side represents a path of ACROBAT1 and the one on the right represents that of ACROBAT2, while the center one shows the midpoint of the two wheels. It is found that approx. 10mm error occurred in Y-direction during the 350mm traveling along the X-direction. The robot motion along the Y-direction is shown in Figure20(b). For realizing this motion, the motors 2 and 3 are commanded to rotate at an identical speed in the same direction. Errors in X-direction are found as well, which is approx. 20mm during 700mm traveling.

Next, a pure rotation motion (pivot turn) was performed by the prototype. Figure20(c) shows the path of the robot in rotation. An over 360degs rotation were tested in which each ACROBAT could not be back to the initial position. Approx.50mm errors are found on both ACROBATs between the initial position and that after 360deg rotation. It is estimated that the errors are caused by differences in the velocity control of motor drivers. Dynamic load changes result in the movement of the center of the robot body because the velocities of the drive wheels can not be maintained to be identical at all times.

Figure20(d) shows the maximum velocity of the robot in 8 directions. By rotating specific motor(s) in the rated speed, resultant robot velocities in the directions are measured from 0deg to 360degs with 45degs increments. It is found that maximum velocities in 45, 135, 225, 315 directions are 1.4 ($\sqrt{2}$) times of the velocities in 0, 90, 180 directions. This result agrees with the analysis of *the Actuation Index* in chapter IV.

Though some motion errors are found on ACROBATs, the fundamental omnidirectional mobility has been verified by the series of the experiments.

VIII. Conclusion

A new omnidirectional robot with ACROBATs and its design method were presented in this paper. The ACROBAT mechanism includes a dual-ball transmission which transmits traction forces from motors to wheel and steering axes via ball to ball contacts. The ball rotation distributes velocity components in appropriate ratio which realize the caster motion of the mechanism. This feature simplifies a robot control system since the advanced servo control based on the orientation of the drive wheel can be removed from the control architecture.

First, the kinematics of the proposed ACROBAT mechanism and a robot with ACROBATs were derived. Next, based on the kinematics, we analyzed the roller layout condition for building the omnidirectional robot with actuated by three motors, namely with no-redundancy.

After *Actuation index* analysis, we determined the two-wheel robot configuration and the drive wheel layout to be located at diagonal positions of the robot frame for maximizing the power production in front direction of the robot.

The prototype of ACROBAT and the robot with two ACROBATs are designed and built. Some fundamental motions and mobile capabilities were tested by the series of experiments. Expected omnidirectional motions were performed by the prototype with a simple control system with a simple robot kinematics and local velocity controllers.

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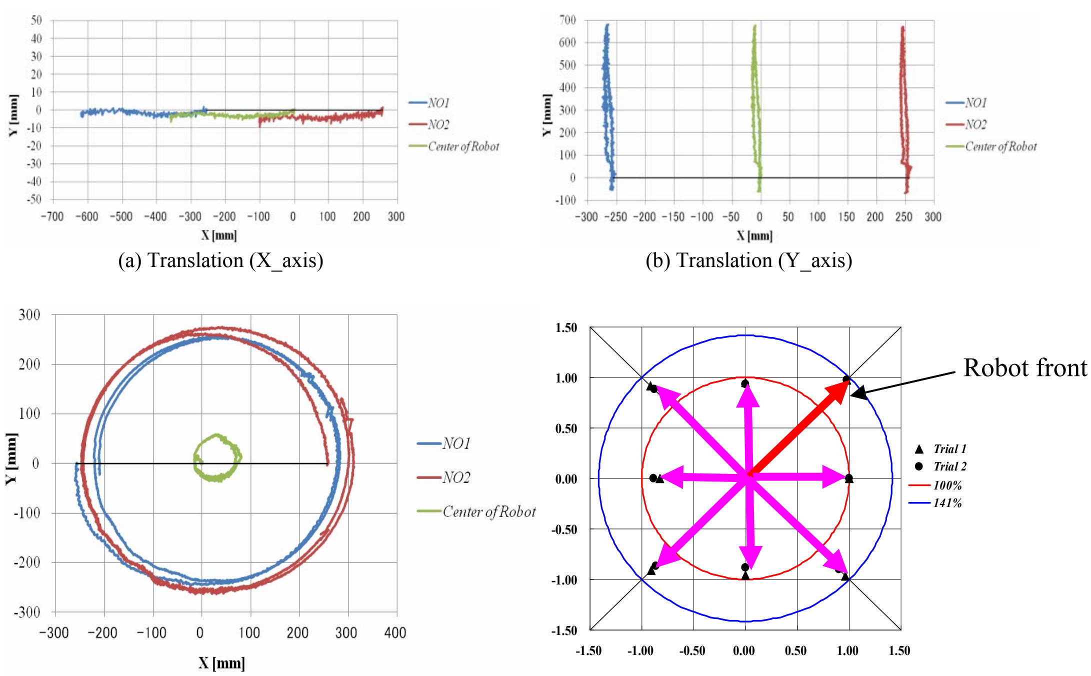

(a) Translation (X_axis)

(b) Translation (Y_axis)

(c) Pivot turn

(d) Maximum velocities in 8-directions of the prototype robot

Figure 20. Experimental results of the prototype omnidirectional robot with ACROBATs