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Paper:

Omnidirectional Mobile Platform for Research and Development

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We detail an omnidirectional mobile platform for research and development (R&D). In 1995, we reported that a special driving mechanism for holonomic omnidirectional mobile robots was designed[1] to enable 3 degree of freedom (DOF) motion control by 3 corresponding actuators decoupled with no redundancy. We constructed a omnidirectional mobile robot prototype with a drive. We took part in a RoboCup tournament[2] as Uttori United with omnidirectional mobile robots: ZEN-450, using our driving mechanism, in 1997, 1998, 1999, and 2000. ZEN-450 showed high mobility during the tournament. However, unpredictable problems occurred because ZEN-450 is not developed for robotic soccer. , We considered improving its hardware as a platform. We report the new platform and test-running results.

Keywords: omnidirectional driving mechanism, RoboCup, platform

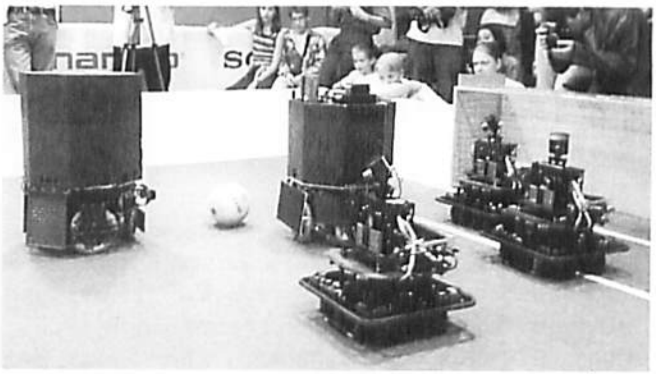

Fig. 1. RoboCup.

1. Introduction

High mobility of platforms is essential to enlarge their applications. Two-wheeled mobile robots have nonholonomic constraints that reduce mobility and make motion planning difficult.

To realize the cooperative motion of mobile platforms, mechanisms for high mobility is required[3], enabling free motion control of each mobile platform. Holonomic omnidirectional mobile platforms provide such high mobility. Though omnidirectional mobile platforms have been proposed, disadvantages have been pointed out for the mechanism and control.

Since 1997, when RoboCup tournament was started competition of focusing on robotics, artificial intelligence and multiagent technologies under real environment. The competition now consists of 4 leagues: simulation, small real robots, middle-size real robots, and legged robots.

We took part in the middle-size real robot league of RoboCup'97 in Nagoya, RoboCup Japan Open'98 in Aoyama, RoboCup'98 in Paris, and RoboCup Japan Open'99 in Nagoya as a united team: Uttori United (Utsunomiya University, Toyo University, RIKEN).

We realized cooperation based on communication among omnidirectional mobile robots: ZEN-450(**Fig.1**). Although the mobility of ZEN-450 was high in the tournament, problems occurred and improvements were needed because ZEN-450 was not developed for robotic soccer competition.

Based on empirical knowledge, we improved platform retaining mobility and developed omnidirectional mobile platform for small Robocup and R&D.

We detail functions and specifications of our omnidirectional mobile platform.

In Section 2, we explain conventional omnidirectional mobile mechanisms and features required for useful platform.

In Section 3, we detail the system configuration and its functions and show basic running experiments using developed platforms.

2. Omnidirectional Mobile Platform

Special wheels with free rollers are used for omnidirectional mobile platforms. Some robots are driven by 3 actuators where wheels are symmetric each wheel axis intersects at 120deg.[4-6] For these platforms, kinematic equation for control is complex because translational and rotational drive by 3 actuators is not decoupled, needing complicated transformation to control the platform in

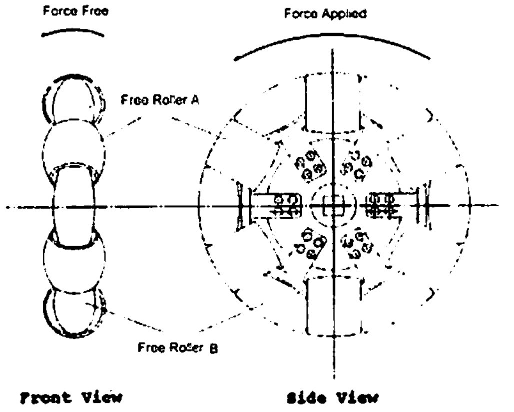

Fig. 2. Structure of a wheel.

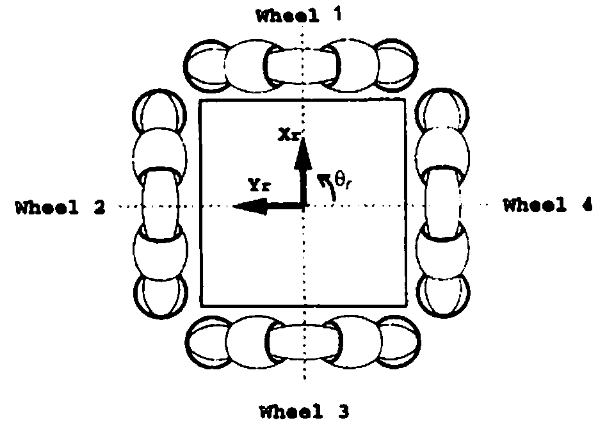

Fig. 3. Arrangement of wheels.

each degree of freedom in Cartesian space. These platforms contact the ground at 3 points and may not be stable in dynamic motion if the center of gravity is high or the robot is small.

Some robots have 4 actuators for 4 wheels[7-9] and redundant DOF. It realizes simple drives. Controlling motors independently requires synchronization among actuators and worsens motion control stability. This redundancy causes control problems where unique output must be determined for controlling the robot in 2 dimensional space and coherent control of 4 wheels is required.

Omnidirectional mobile robots driven by spherical actuators have trade-off problems between friction and slip and in down-sizing.[6,10] We developed an original omnidirectional mobile mechanism in 1995.[1] A mobile robot with this mechanism is a standard experimental platform in our research group. We studied how to improve our platform.

Important platform factors are lightweight, high electrical efficiency, and easy maintenance or maintenance-free. Easy monitoring of the platform's status is also required. Developing easily operated platforms supports R&D for social applications.[11,12]

3. Mobile Platform: ZEN-360

3.1 3 DOF Decoupled Driving Mechanism

To overcome the problems in the previous section, we designed a 3 DOF decoupling drive for holonomic omnidirectional mobile robots, enabling us to drive 4 wheels by 3 actuators for corresponding DOF.

Figure 2 shows the wheel, whose basic concept is based on arrangement of aligned free rollers to structure a wheel, which has been proposed associated with omnidirectional mobile robots. Twelve barrel-shaped free rollers are arranged symmetrically so the external curve of rollers for a plane perpendicular to the axle is equal to wheel curvature. The distance from the axle to any peripheral point of rollers is constant, i.e., the wheel radius.

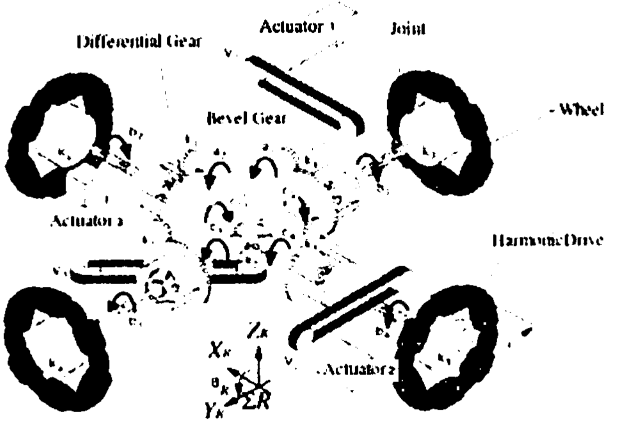

Fig. 4. Transmission mechanism of our platform.

The envelope shape of rollers in the assembly, arranged on the wheel periphery, covers the circumference of a wheel circle, making the wheel contact the ground at a distance constant from the axle at any moment when the wheel is revolving about the axle. The friction of free rollers is small enough so wheel drive is applied to the ground only forward and external force in the axle direction is released by free rollers.

Figure 3 shows the arrangement of 4 wheels. Translational motion along X_r is generated by driving wheels 2 and 4, and that along Y_r is generated by driving wheels 1 and 3. Translational motion in any direction is produced by translational motion along X_r and Y_r. Rotation about Zr is driven by all 4 wheels rotating in the same direction.

Figure 4 shows the transmission mechanism of the omnidirectional mobile robot. The actual robot coordinates are located in the center of the robot.

With this mechanism, 3 DOF motion, 2 DOF translational motion along X- and Y-axis and 1 DOF rotation about Z-axis is mechanically decoupled to be driven with no redundancy. The 4 wheels are driven by 3 actuators, each of which drives wheels to move the robot for a certain DOF. The driving force of actuator 1 is transmitted to the shaft (a_1) via a pulley and revolves spur gears

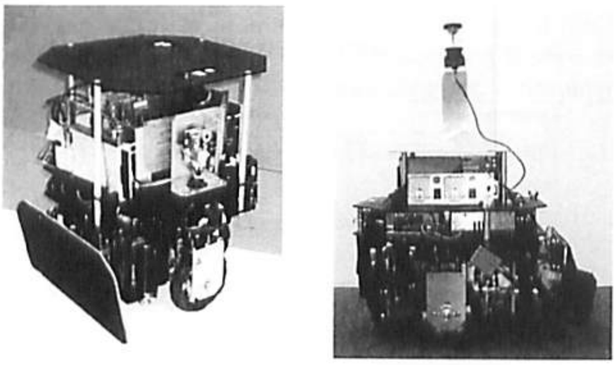

Fig. 5. Overview of an omnidirectional mobile platform.

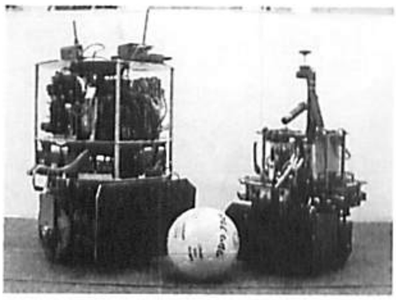

Fig. 6. ZEN-450 and 360 as RoboCup-type platform.

Table 1. Supecification of I/F board.

Function	Channel	Spec.
A/D	16ch	12 bit (-10-+10[V])input
D/A	16ch	12 bit (-10-+10[V]) output
PIO	16ch	128 bit input/output
Counter	16ch	24 bit pulse counter
PWM	16ch	1/256 resolution

2 and 4, which rotate wheels 2 and 4 via differential gears 2 and 4 to translate the robot toward X_r. This way, actuator drive 2 contributes translational motion to Y_r. Actuator drive 3 revolves 4 shafts (c_1,c_2,c_3,c_4) through the pulley and bevel gear, which rotates 4 wheels in the same direction. When the robot translates with rotation, differential gears produce the required velocity difference between 2 wheels in each translational direction. Kinematics are detailed in the Appendix.

Based on our mechanical design, a prototype robot was developed. **Fig.5** shows a platform overview. The one at right uses a conventional CCD camera and that at left uses omnidirectional vision. Abstract specifications of ZEN-360 are as follows:

Size: W:360xD:360xH:610mm
Weight: 19.5kg
Maximum Velocity: 257.5mm/s(translation)
18.21 deg/s(rotation)
Wheel: 130mm

For reference, the specifications of ZEN-450 are 450ö 450 ö 640mm, 50.0kg, 400mm/s, 45deg/s, and wheel size is 200mm.

Fig. 7. Example motion 1.

Fig. 8. Example motion 2.

Fig. 9. Example motion 3.

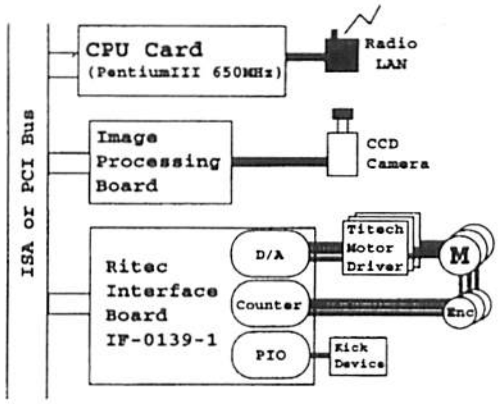

Fig. 10. Control system.

Suspension mechanisms are used for each wheel, so all wheels contact the ground evenly in varied terrain locomotion. This suspension guarantees wheel contact with the ground with the direction of the axle horizontal. To verify motion of the omnidirectional mobile platform with a 3 DOF decoupled drive, 3 DC-motors were used for actuators, and sample motions used to drive corresponding motors. Results of sample motions below are shown in **Figs.7-9**, where realized trajectories are shown:

Sample motion 1 Straight translation along X_r by driving actuator 1 only, then straight translation along Y_r by driving actuator 2 only, and then straight translation along X_r by driving actuator 1 only.

Sample motion 2 Straight translation along X_r by driving actuator 1 only, then straight translation at an angle

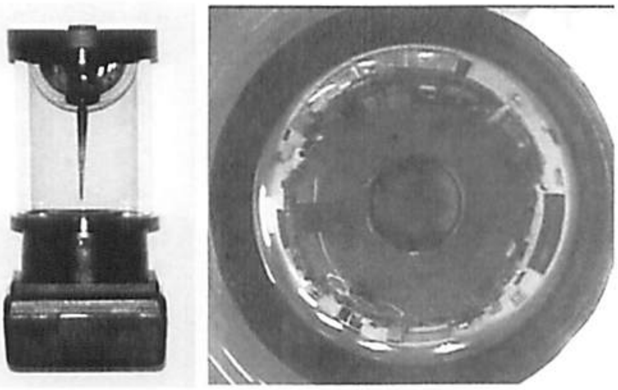

Fig. 11. Camera with omni-lens and an example image.

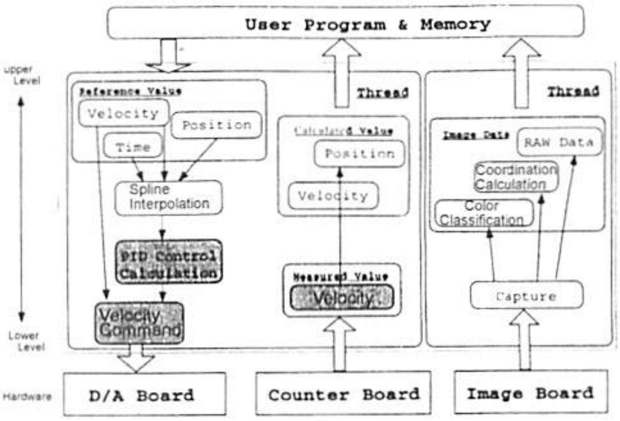

Fig. 13. Software structure on Linux OS.

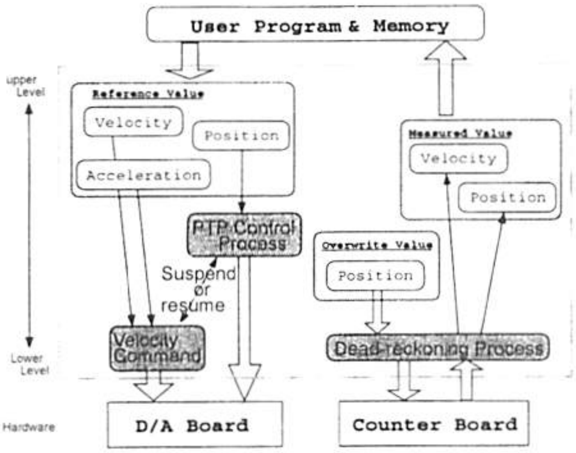

Fig. 12. Software structure on VxWorks OS.

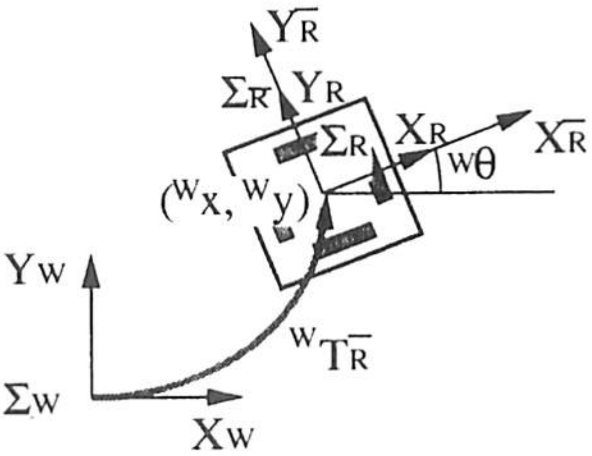

Fig. 14. Coordinate systems.

of 45 degree from X_r and Y_r by driving actuator 1 and 2 simultaneously, and then straight translation alongX_r by driving actuator 1 only.

Sample motion 3 Rotation about Z_r without translation by driving actuator 3 only.

3.2. Control System

Basic control on ZEN-360 is shown in **Fig.10**. It consists of a CPU card, I/O for control, and image processing. For control equipment, we use a half-size CPU card(e.g., prototype Intel Pentium III 650MHz and RITEC interface Board,[13] which we joined to development instead of using multiple I/O cards. **Table 1** details specifications of the RITEC Interface Board. The TITECH driver, which Prof. Hirose et al. of the Tokyo Institute of Technology developed,[13] is used as the motor driver. The motor command is send to the TITECH driver via a D/A port on the RITEC interface card. The output of encoders on each motor is stored via a counter port on the interface board. It is possible to connect multiple sensors via the A/D, PIO, and counter port on the interface card. More actuators are connected to D/A and PWM ports.

As an example, for the standard sensor on our platform, we used a camera (visual sensor).

It is for RoboCup tournaments. We installed an omnidirectional visual sensor for effective exploiting omnidirectional mobility.

Figure11 shows a camera with commercial omnidirection.[14] We used another conventional CCD camera with the omnidirectional one in the RoboCup tournament.

3.3. Software

ZEN-450 uses C and a commercial real-time OS, VxWorks, as the software development environment.

The software structure for motion control on VxWorks is shown in **Fig12**. Each process is supervised using semaphore and priority. One control period is 20ms.

Image processing is not specialized, using sequential processing (image capturing, filtering, and labeling) and is running with a control process.

We considered introducing a free PC-Unix OS, Line (Linux Ver 2.1), and developing software using C for ZEN-360. We provided basic functions (software programs) for control and sensing. They helps the developer's work by easy operation. Typical sample functions are for driving the motor (PID controller), capturing images, and color calibration. On Linux OS, a P (POSIX) thread as UNIX standard parallel processing is used and the drive motor and image processing are independent threads (**Fig.13**).

We consider developing software on multiple OSs (DOS, RT-Linux, ART-Linux, VxWorks, etc.). We will make a standard program library for this mobile platform.

4. Conclusion

We described our omnidirectional mobile platform for R&D. Our platform was improved based on our experience and precedents in experiments for research, demonstration at exhibitions, and RoboCup tournaments. We will further improve a platform for easy operation with high mobility. Uttori United took part in the RoboCup Japan Open in 2001 using this platform and demonstrated its efficiency. In 2002, we plan to participate in the RoboCup International Tournament at Fukuoka with our platform and a strategy using message exchange in a robot soccer environment.[15)]

Appendix

Kinematics in a Robot Coordinate Frame

Three coordinates are assumed (**Fig.14**). Σ_w, Σ_r and Σr indicate world coordinates, robot coordinates, and robot instantaneously coincident coordinates. Robot instantaneous coincident coordination is a Frame.[17)] The following equations on relation between rotational velocities of shafts in **Fig.4** are derived:

$$a_1 = k_1 V_1$$
$$a_2 = k_1 V_2$$
$$c_1 = c_2 = c_3 = c_4 = k_3 V_3$$

From this differential gear mechanism, the following equations are derived:

$$-2k_2 a_1 = b_1 + c_1$$
$$2k_2 a_2 = b_2 + c_2$$
$$2k_2 a_1 = b_3 + c_3$$
$$-2k_2 a_2 = b_4 + c_4$$

where k_1, k_2, k_3 are reduction ratios of pulleys, spur gears, and bevel gears. Solving these equations yields the velocity of each axle as follows:

$$b_1 = -2k_1 k_2 V_2 - k_3 V_3$$
$$b_2 = 2k_1 k_2 V_1 - k_3 V_3$$
$$b_3 = 2k_1 k_2 V_2 - k_3 V_3$$
$$b_4 = -2k_1 k_2 V_1 - k_3 V_3$$

Let r and T be the radius of wheels and half tread (distance from the center of the robot to the center of the wheel).

${}^{\bar r}\dot{\mathbf{P}} = [\,{}^{\bar r}\dot{x}, {}^{\bar r}\dot{y}, {}^{\bar r}\dot{\theta}\,]^T$, the velocity of the robot relative to $\Sigma_{\bar r}$, is represented as follows:

$${}^{\bar r}\dot{\mathbf{p}} = \begin{pmatrix} 2k_1 k_2 r & 0 & 0 \\ 0 & 2k_1 k_2 r & 0 \\ 0 & 0 & k_3 \frac{r}{T} \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \\ V_3 \end{pmatrix}$$

$$= {}^{\bar r}\mathbf{J}\dot{\mathbf{q}} \quad \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

${}^{\bar r}\mathbf{J}$ denotes a Jacobi matrix for $\Sigma_{\bar r}$, and $\dot{\mathbf{q}}$ denotes the velocity of actuators. Since ${}^{\bar r}\mathbf{J}$ is a diagonal matrix, translational motion in each direction or robot rotation for $\Sigma_{\bar r}$ is decoupled and driven by corresponding actuators.

Kinematics with Coordinate Transformation

We assume planar pairs for coordinate transformation between 2 frames, i.e., between Sw and $\Sigma_{\bar r}$ between $\Sigma_{\bar r}$ and Σ_r. The transformation matrix (2 dimensional homogeneous coordinate transformation) relating Σ_w to $\Sigma_{\bar r}$, is as follows:

$${}^{w}\mathbf{T}_{\bar r} = \begin{pmatrix} \cos{}^{w}\theta & -\sin{}^{w}\theta & {}^{w}x \\ \sin{}^{w}\theta & \cos{}^{w}\theta & {}^{w}y \\ 0 & 0 & 1 \end{pmatrix}$$

Since Σ_w and $\Sigma_{\bar r}$ are stationary, the derivative of this matrix as a function of time is zero.

$${}^{w}\dot{\mathbf{T}}_{\bar r} = \mathbf{0}$$

For position **p**, the following transformation equation is defined:

$${}^{w}\mathbf{P} = {}^{w}\mathbf{T}_{\bar r}\,{}^{\bar r}\mathbf{p}$$

By substituting transformation matrices and Eq.(1) into the derivative of the equation above, the following forward kinematic equation is obtained:

$${}^{w}\dot{\mathbf{p}} = {}^{w}\mathbf{T}_{\bar r}\,{}^{\bar r}\dot{\mathbf{p}} = {}^{w}\mathbf{T}_{\bar r}\,{}^{\bar r}\mathbf{J}\dot{\mathbf{q}} = {}^{w}\mathbf{J}\dot{\mathbf{q}} \quad \cdots\cdots\cdots\cdots (2)$$

where ${}^{w}\mathbf{J}$ is the Jacobi matrix for Σ_w obtained as follows:

$${}^{w}\mathbf{J} = {}^{w}\mathbf{T}_{\bar r}\,{}^{\bar r}\mathbf{J}$$

$$= \begin{pmatrix} 2k_1 k_2 r\cos{}^{w}\theta & -2k_1 k_2 r\sin{}^{w}\theta & k_3 \frac{r}{T}{}^{w}x \\ 2k_1 k_2 r\sin{}^{w}\theta & 2k_1 k_2 r\cos{}^{w}\theta & k_3 \frac{r}{T}{}^{w}y \\ 0 & 0 & k_3 \frac{r}{T} \end{pmatrix}$$

The inverse kinematic equation is obtained from Eq.(2) as follows:

$$\dot{q} = {}^{w}J^{-1}\,{}^{w}\dot{p} = {}^{\bar{r}}J^{-1}\,{}^{w}T_{\bar{r}}^{\;-1}\,{}^{w}\dot{p} \quad \ldots\ldots\ldots\ldots \quad (3)$$

where

$${}^{w}J^{-1} = {}^{\bar{r}}J^{-1}\,{}^{w}T_{\bar{r}}^{\;-1}$$

$$= \begin{pmatrix} \dfrac{\cos{}^{w}\theta}{2k_1k_2r} & \dfrac{\sin{}^{w}\theta}{2k_1k_2r} & \dfrac{-{}^{w}x\cos{}^{w}\theta - {}^{w}y\sin{}^{w}\theta}{2k_1k_2r} \\ -\dfrac{\sin{}^{w}\theta}{2k_1k_2r} & \dfrac{\cos{}^{w}\theta}{2k_1k_2r} & \dfrac{{}^{w}x\sin{}^{w}\theta - {}^{w}y\cos{}^{w}\theta}{2k_1k_2r} \\ 0 & 0 & \dfrac{T}{k_3r} \end{pmatrix}$$

The velocity of actuators is obtained by substituting into Eq.(3) the required translational and rotational velocity; ${}^{w}\dot{x}$, ${}^{w}\dot{y}$, ${}^{w}\dot{\theta}$, and the current position and orientation; ${}^{w}x$, ${}^{w}y$, ${}^{w}\theta$, for Σ_w.

References:

1) H. Asama, M. Satoh, H. Kaetsu, A. Matsumoto, 1. Endo, "Development of an Omni-Directional Mo-bile Robot with 3 DOF Decoupling Drive Mech anism", Proc. of Int. Conf. on Robotics and Au-tomation, pp.1925, 1995.
2) http://www.robocup.org/
3) Distributed Autonomous Robotic Springer-Verlag.
4) F. G. Pin, S. M. Killough, "A New Family of Om-nidirectional and Holonomic Wheeled Platforms for Mobile Robots", IEEE Trans. on Robotics and Automation, 10, 4, pp480, 1994.
5) B. Carlisle, "An Omnidirectional Mobile Robot", Development in Robotics, IFS Publishers Ltd., 1983, 79.
6) M. West, H. Asada, "Design of Ball Wheel Vehi-cles with Full Mobility, Invariant Kinematics and Dynamics and Anti-Slip Control", Proc. of ASME Design Technical Conference, 23rd Mechanisms Conference, 1994.
7) P. F. Muir, C. P. Neuman, "Kinematic Model-ing for Feedback Control of an Omnidirectional Wheeled Mobile Robots", Proc. of Int. Conf. on Robotics and Automation, pp.1772, 1987.
8) B. Rembold, "Kinematic Control of a Mecanum Wheel based Omnidirectional Mobile Platform", Proc. of 2nd Workshop on Manipulators, Sensors and Steps to Mobility, 1988.
9) S. Hirose, S. Amano, "The VUTON: High Payload, High Efficiency Holonomic Omni-Directional Vehicle", Proc. of Int. Symp. on Robotics Research, 1993.
10) M. West, H. Asada, "Design of a Holonomic Omnidirectional Vehicle", Proc. of International Conference on Robotics and Automation, pp.97, 1992.
11) S. Mascaro, H. Asada: "Docking Control of Holonomic Omnidirectional Vehicles With Ap-plications to a Hybrid Wheelchar/Bed System", Proc. of Int. Conf. on Robotics and Automation, pp.399-405, 1998.
12) M. Wada, H. Asada: "A Holonomic Omnidi-rectional Wheelchair with a Variable Footprint Mechanism", Proc. of Int. Conf. on Advanced Mechatronics, pp.268-274, 1998.
13) http://www.okatech.com/
14) http://www.pluto.dti.ne.jp/accowlel
15) K. Yokota, K. Ozaki, A. Matsumoto, K. Kawa-bata, H. Kaetsu, H. Asama : Omni-directional Autonomous Robots Cooperating for Team Play, Proc. of the Second RoboCup Workshop, pp491-496, 1998.
16) H. Asama, A. Matsumoto, Y. Ishida, "Design of an Autonomous and Distributed Robot System: ACTRESS", Proc. of Int. Workshop on Intelli-gent Robots and Systems, pp.283, 1989.
17) P. F. Muir, C. P. Neuman, "Kinematic *Modeling* of Wheeled Mobile Robots", Journal of Robotic Systems, 4, pp.2281, 1987..

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