DESIGN OF AN OMNIDIRECTIONAL ROBOT FOR FIRA ROBOSOT

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ABSTRACT

The paper describes the design process of building an omnidirectional robot team for FIRA Robosot. The robots are designed to be omnidirectional for increased mobility and possess omnivision capabilities for effectiveness. Wheel configurations are discussed and the kinematics of the final design are derived. The vision system is described along with the basic vision processing technique including a proposed color space algorithm, the Diff RGB. The complete system architecture is presented with components of the drive mechanisms and electronics being detailed. The final mechanical design for the omni-drive and the robot is then presented.

1. INTRODUCTION

The last few years have evinced rapid progress and developments in mobile robot technology. While this growth is partly owing to developments in the many allied research areas such as electronics, vision systems and drive systems, competitive events also have contributed their part to this progress through competitions such as the FIRA championship. Robot soccer has shown itself to be an ideal testbed for state-of-art technologies in robotics.

FIRA Robosot is an integral component of the FIRA robot-soccer championships. It was initiated with the aim of promoting research in autonomous wheeled mobile robot technology. It is a game of robot soccer played between two teams of autonomous intelligent wheeled mobile robots on a field. Robots are permitted to carry on board sensors including vision systems, however global vision systems are disallowed. Communications (if any) is allowed through wireless between the robots and a remote host computer. These restrictions present an interesting challenge for prospective teams by requiring intelligent robots which individually must possess proficient vision abilities in addition to high performance speeds, in both processing and drive mechanisms [13]. The robots must also be capable of interacting and performing as a team [11], [14].

Many researchers have attempted the design of highly maneuverable robotic platforms. In this regard, the OmniKity series of robots [1], developed at the RIT Lab were used for earlier Robosot competitions. These robots had many attractive features such as an omnidirectional, fault tolerant differential drive and simple and compact mechanical structure. However its primary drawback was its speed. In this regard, robots using mecanum wheel platforms, as surveyed in Section 2, present an effective alternative.

This paper discusses the design of a high speed, highly maneuverable robot which is holonomic omnidirectional, using mecanum wheels, and equipped with omnidirectional vision capabilities. The vision system and its basic algorithm is also presented. A new color space for vision algorithm is also proposed. The robot itself is intended to be used as a part of heterogenous team of autonomous robots for Robosot. This paper is organized as follows. Section 2 discusses the salient features of the motion platform. Section 3 explains the vision system. The complete architecture and its design are detailed in Section 3 followed by the conclusion

2. MOTION PLATFORM

2.1. Omnidirectionality

A prerequisite feature desired in the design of a robosot player is the ability to maneuver quickly and efficiently to any position regardless of its current posture. Ideally, we wish it to be free of the typical constraints imposed by the no-slip condition in the direction of the transverse axis for a conventional wheel. There are several designs that allow for this level of maneuverability and such designs are defined as being *omnidirectional*. A stricter definition of the term requires that there exist a set of wheel spins and (for some designs) steering velocities that permit any desired set of velocities in the space of possible robot motions.

2.2. Steerable Wheel Designs

There are various configurations [1, 2] which utilize steerable wheels to provide omnidirectional capability. These involve making a change to the chassis configuration/internal

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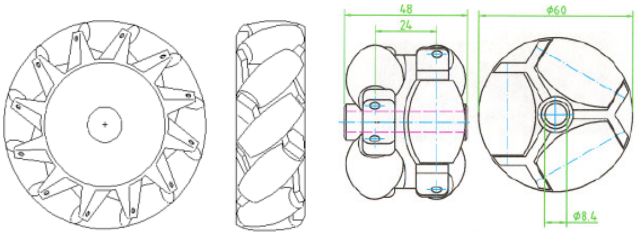
This work was funded by the Ministry of Information and Communications, Korea under the ITRC (Intelligent Robot Research Center) Support Program.

state of the robot to enable a change in the velocity in any chosen direction. Although holonomic, they do have some drawbacks. To facilitate some motions, the steering mechanism necessitates a change in the internal state of the robot. This change takes a finite time and small changes in motion do not necessarily correspond to small changes in the internal state. For some mechanisms there may also be some small amount of slip (a realistic wheel contact is a contact line rather than a single point) especially if the robot is already in motion.

2.3. Mecanum Wheel Designs

An alternative design uses the Swedish, or Mecanum wheel. The mecanum wheel removes the transverse no-slip constraint by utilizing the free spinning rollers to allow unconstrained motion along the transverse axis. The orientation of the transverse axis can be further manipulated orienting the rollers accordingly as illustrated in Figure 1a. Often, the rollers are aligned perpendicularly as in Figure 1b. In this case the wheel is configured as a symmetrically offset pair so contact with the ground is always maintained without discontinuity. This design is often generically referred to as an *omniwheel* and is widely available commercially.



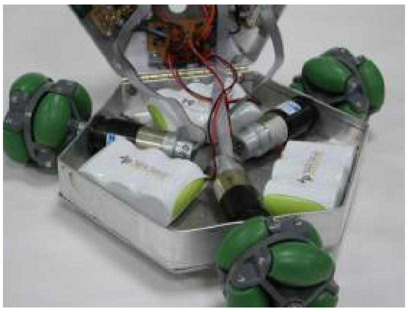
a) Mecanum Wheel b) Omniwheel

Figure 1: Mecanum Wheels

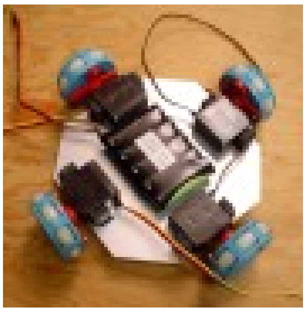
Mecanum wheels do not have the drawbacks listed above that characterize steered omnidirectional designs. Small changes in motion are at all times accompanied by small changes in motor torques and the internal state does not need to be reconfigured. They do have one drawback however, frictional forces in the transverse direction cannot be utilized to generate the centripital forces for motion along a curve. These forces must be solely generated by the motors and this can place an undesirable demand on the power supply. Nevertheless, maneuverability was deemed to be a higher priority for the project and the decision to utilize a mecanum wheel design was made.

2.4. 3 vs 4 Wheel Design

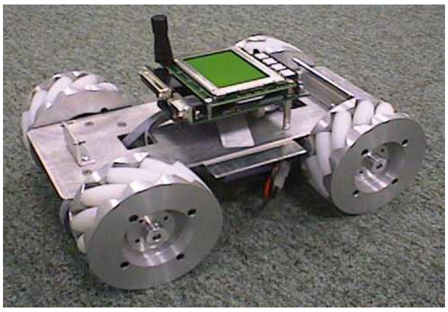
The minimum number of wheels required for static stability is three (unless the center of mass can be shifted below the wheel axis). Theoretically a three wheel design such as that shown in Figure 2a will offer greater traction as the reaction force is distributed through only three points as opposed to four. This advantage however, could be offset by tilting instabilities - practical testing within the robosot environment would be required.da Note that the four wheel design in Figure 2c is often utilized to take advantage of more conveniently arranged motor placements on a small platform.



a) 3 omniwheel



b) 4 omniwheel



c) 4 mecanum wheel

Figure 2: 3 vs 4 Wheel Designs

2.5. Omniwheel Kinematics

2.5.1. Global and Local Reference Frames

The kinematics provides a means of converting between global posture co-ordinates and internal configuration. In order to specify the global position of the robot, a relationship is established between the global reference frame (X_G, Y_G) and an instantaneous local frame centred on the robot (X_R, Y_R). The posture of the robot is given by $\xi_G = [x, y, \theta]^T$. Mapping motions between local and global frame is related simply by a rotation matrix (remembering the lo-

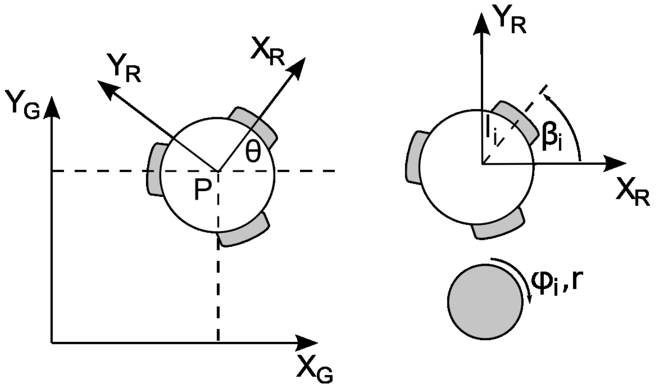


Figure 3: Reference Frames

cal frame here is fixed and not rotating with the robot).

$$\dot{\xi}_R = R(\theta)\dot{\xi}_G \qquad \text{where} \qquad R(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

2.5.2. No-Slip Constraint

With the mecanum wheels aligned radially around the robot as illustrated in Figure 3, the no-slip condition for the i-th wheel is given by (refer to [3]):

$$[\sin(\beta_i) \;\; -\cos(\beta_i) \;\; (-l_i)]\, R(\theta)\dot{\xi}_G - r\dot{\varphi}_i = 0 \qquad (1)$$

2.5.3. Kinematics

Rewriting (1) in matrix form yields the kinematics equations for the robot

$$\dot{\xi}_G = R(\theta)^{-1} J_{1f}^{-1} J_2 \dot{\varphi},$$

where J_{1f} is the matrix of rolling constraints and J_2 holds the wheel radii. Under most configurations this equation can be inverted for a unique determination of the inverse kinematics. Although not trivial, it is possible to show with these equations that maximum velocities can be achieved with a symmetrical configuration. Given wheel placements at $(\beta_1, \beta_2, \beta_3) = (\pi/3, \pi, -\pi/3)$, maximum speed of the robot is given by

$$v_{max} = \frac{2}{\sqrt{3}} v_{wmax}$$

where v_{wmax} is the maximum wheel speed. This is significantly greater than the speed obtainable by a generic four wheeled differential drive configuration due to the contribution from motion generated on the transverse axis of each wheel. Acceleration however is reduced as the torques and forces generated by the wheels do not act in parallel.

2.6. Control Schemes

Control schemes must be implemented to ensure a trajectory through the global workspace can be tracked. There are many ways to develop a control algorithm for this task. A simple feedback control law such as that illustrated in [2] can be utilized to track a desired trajectory however, the control law we use will implement a form of terminal sliding mode control [4], [12]to provide a degree of robustness to uncertainty and ensure finite time tracking of trajectory tasks.

2.7. Navigation

In the hierarchy of motion design, navigational path planning is at the highest level. Trajectories must be planned through the environment which are then passed to the controllers to ensure they are tracked. Since our primary short term goal is to develop a functional set of robots, navigational path planning will be restricted to a few simple necessary techniques.

3. VISION SYSTEM

3.1. Vision Hardware

As stated earlier, the robot employs the Omnidirectional Vision System. This vision system provides the entire playground image thereby simulating a global vision system, similar to those employed in Mirosot. Using the image of the entire field, the robot localization can be performed. There are two primary kinds of omnidirectional vision systems available commercially. The first system, similar to the one in Figure 4a, is a catadioptric vision sensor using a single camera and a specially shaped mirror. The system in Figure 4b, is polydioptric and however uses multiple vision sensors. The former requires carefully tuning and calibration of the vision software. It may not always be appropriate for the dynamic soccer robots. The camera in Figure 4b is the Point Grey Ladybug which is the camera chosen for the current architecture. Ladybug has five side-view cameras and one top-view camera. The Ladybug thus obtains images covering 80% of a sphere.

3.2. Constant Intensity Color Space : Diff RGB Color Space

In color image processing, changes in illumination, intensity of object, and shadow make color detection a difficult task. There are a number of researchers working towards minimizing these harmful effect. One well known approach is the usage of a color space different from that of RGB color space. Because each component of RGB color space is highly correlated to intensity, [5], [6], and [7] use (S, I), (U, V), and (Cb, Cr) components in HSI, YUV, and YCbCr color space. And [8], [9], and [10], use normalized RGB color space. Normalized RGB color space is a simpler variant of RGB color space.

Definition 1 : Normalized RGB Color Space Let $(R, G, B) \in$ RGB Color Space, $(r, g, b) \in$ Normalized RGB Color Space,

a) Catadioptric vision sensors

b) Polydioptric vision sensors

Figure 4: Omnidirectional Vision Systems

$$\begin{aligned} r &= R/(R+G+B) \\ g &= G/(R+G+B) \\ b &= B/(R+G+B) \end{aligned} \qquad (2)$$

Definition 2 : Intensity of RGB Color Space Let $(R, G, B) \in$ RGB Color Space, $Intensity = (R + G + B)/3$

In RGB color space, Intensity is defined as in *Definition 2*. Eq. 3 means that normalized RGB is mapping from whole RGB color space to constant intensity plane. But normalized RGB has a singular point at $(R, G, B) = (0, 0, 0)$. And time-consumed floating-point operations are needed to transform RGB to normalized RGB.

$$intensity = (r + g + b)/3 = 1 \qquad (3)$$

So we propose a new color space, Diff RGB, which is faster and safer than normalized RGB.

Definiton 3 RGB Color Space to Diff RGB Color Space Let $(R, G, B) \in RGB$ Color Space, $(r', g', b') \in$ Diff RGB Color Space,

$$\begin{aligned} r' &= R - G \\ g' &= G - B \\ b' &= B - R \end{aligned} \qquad (4)$$

Eq. 5 means that Diff RGB also has constant intensity property as like normalized RGB. Figure 5 shows intensity-varying color bars, its normalized RGB result, and Diff RGB. It can be seen that, normalized RGB and Diff RGB reduce the effect of intensity variation. In addition, Diff RGB does not have any singular point, so there are no black bands especially in the lower regions, in the Diff RGB color bars.

$$intensity = (r' + g' + b')/3 = 0 \qquad (5)$$

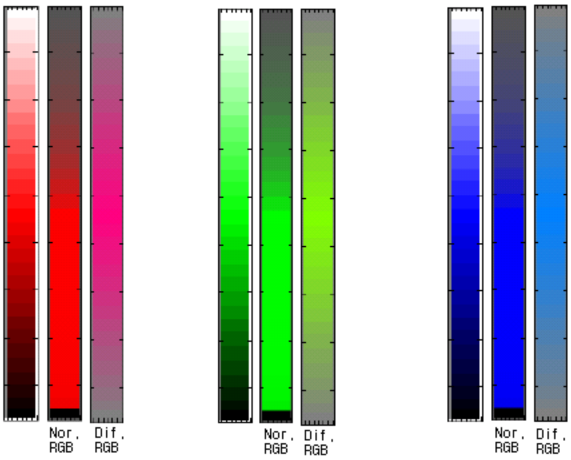


Figure 5: Intensity-varying Red, Green, and Blue Bar

Diff RGB is about six times faster than normalized RGB since it utilizes only integer subtraction.

3.3. Localization using Omnidirectional Vision System

Omnidirectional vision system obtains image from all around the robot. But however, it is a side-view image and not a top-view image as like MIROSOT. So, calculation of its global position (x, y, θ) is not easy. But using the six markers present on the field(four poles and two goalpost), the robot can estimate its global position. Localization algorithms are designed under following four assumptions.

1. The robot knows the position of six markers.
2. The robot can distinguish each marker using their inherent shape and geometrical relationship.
3. The robot can calculate global orientation component θ using any one of the markers.
4. Each image obtained by the robot has at least three markers for localization.

The general localization scenario is shown in Figure 6 using three markers. Eq 6 may thus be obtained using the second cosine law.

$$\begin{aligned} (x3 - x2)^2 + (y3 - y2)^2 &= a^2 + b^2 - 2abcos(\theta 2) \\ (x2 - x1)^2 + (y2 - y1)^2 &= b^2 + c^2 - 2bccos(\theta 3) \end{aligned} \qquad (6)$$

The localization may thus be performed as in Eq. 6. However the inherent complexity of the computation demands

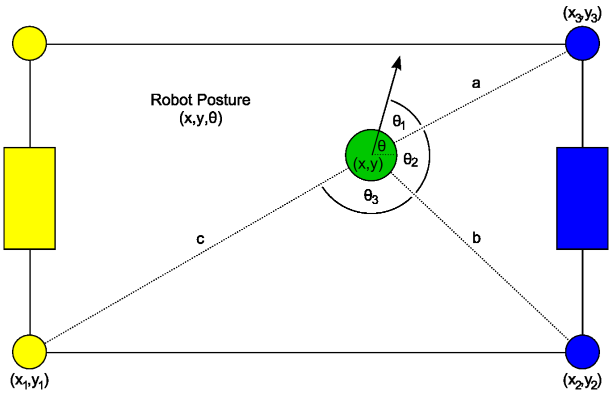


Figure 6: General localization scenario

that some optimization be employed. Currently, approaches using look-up tables, hash-tables, and approximated geometric solutions are being implemented and tested for their feasibility.

4. ARCHITECTURE AND DESIGN

The robot has been designed as shown in Figure 7. The architecture is modular and and may be broadly classified into vision hardware, onboard electronics, notebook PC primary controller and the mechanical structure.

4.1. Electronics and Drive

The drive mechanism consists of high power DC motors and these require onboard electronics custom designed to control them effectively. The drive and electronics system is discussed in greater detail in the following sections.

4.1.1. Onboard Electronics

The primary function of the onboard electronics is to perform real-time motor control and power supply for the camera system. The motor controller circuitry as shown in Figure 7 has been designed using the TMS320F2811 DSP for high speed and real time operation. The firmware of the DSP runs the feedforward control of the motors using the digital PD algorithm. It also additionally incorporates the inverse kinematics to convert higher level global motions into individual wheel spins. The system draws power from a battery pack consisting of lithium polymer cells giving a battery life of about 45 minutes.

4.1.2. Drive Mechanism

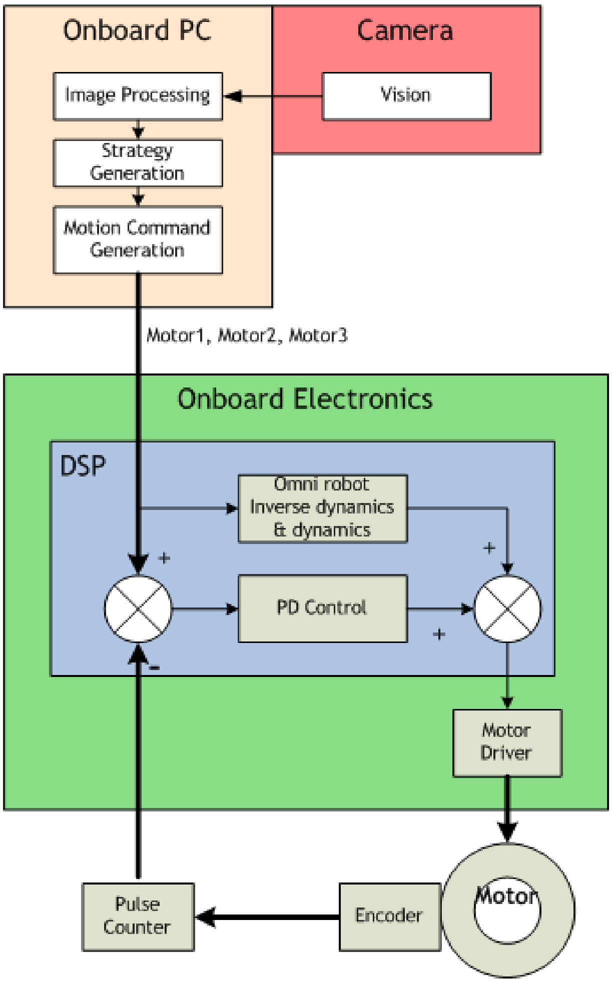


Figure 7: The system architecture

The primary drive mechanism for the robot is a set of three $200W$ brushless DC motors. These are high power motors chosen to maximize the acceleration and top speed of the robot. A detailed analysis of motor response was performed to determine the best configuration of motor, gears, and belt drive to maximize robot performance. The choice was dictated by a design stipulation of acceleration exceeding $3m/s^2$ and top speed of over $3m/s$. The performance was incorporated along with the platform kinematics and was analyzed at different motor conditions. The final configuration incorporates the motors with a fixed gear head. The belt drive mechanism allows 4 possible gear ratios to be used, which provides flexibility in the final configuration, to be applied under various circumstances as determined by actual loading conditions and surface slip.

4.2. Mechanical Design

Based on the platform kinematics and the motor choice, the robot was designed as shown in Figure 8. The design was made for the Ladybug camera system, with the possibility of attachment of a catadioptric omnidirectional vision sensor instead, and contains a custom designed omnidrive mechanism on an omnidirectional platform base. The complete mechanical design process took a period of 3 months, in which an iterative process was followed with frequent cycles of analysis and redesign.

The primary challenge to the design team was to pro-

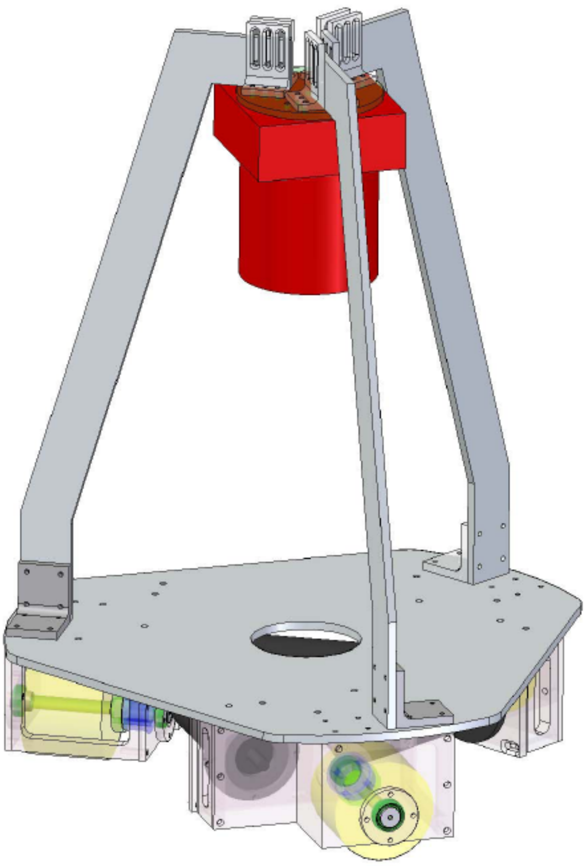
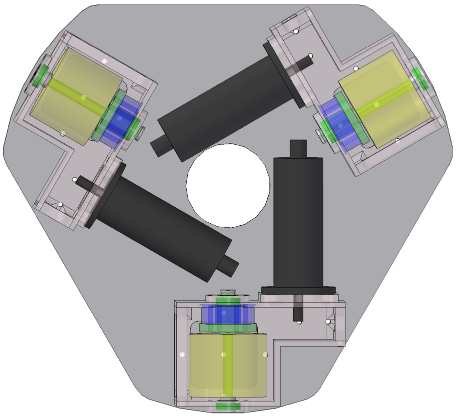


Figure 8: The Robot

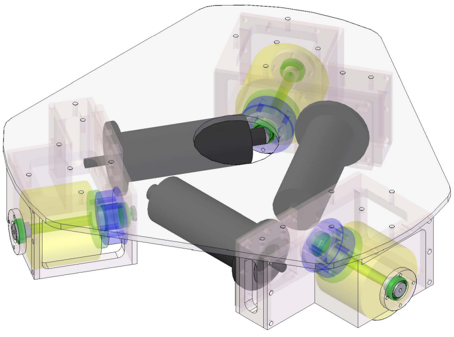
vide a design accommodating the large components such as the motors, omniwheel drive mechanism, notebook PC, and the Ladybug camera within the compact space as stipulated within the size restrictions of the Robosot. The structure of the omni-drive and the platform is shown in Figure 9. The omni-drive was first designed using a high strength cage structure with a mechanism for gear ratio change. This permits a high level of flexibility as the gear ratios can be adjusted to achieve the desired performance without necessitating any design changes. The platform shape has been designed to be in the form of a triangle with flat faces aiding in striking the ball and rounded edges for safety in collisions.

The configuration portrayed in Figure 8 shows the ladybug camera in inverted configuration. This particular configuration maximizes the view of the entire field by also providing high quality images in the vicinity of the robot. The configuration has however been designed to provide minimal obstruction to the vision system through the usage of frame mounts for the Ladybug, which requires firm mountings on account of its weight.

The design was made considering Duraluminium as the build material, on the basis of its strength. Due consideration however has been made for keeping the robot as light as possible.



a) Omni-Drive



c) Omnidirectional Platform

Figure 9: Omnidirectional Platform and Drive

5. CONCLUSION

The paper discussed the complete design process of the omnidirectional robot for FIRA Robosot. The kinematics of the omni-directional platform were examined. The vision algorithm was detailed and the effectiveness of the proposed color mapping, the Diff RGB was amply demonstrated. The basic localization scenario was also briefed upon. The complete system architecture and design of the electronics, drive systems and the mechanical design were presented. The drive system and electronics were shown to be designed keeping speed and mobility in mind. The advantages of the mechanical design particularly in terms of efficient space usage and modularity were discussed. It is hoped that the extensive design process results in an highly effective robot for FIRA Robosot.

6. REFERENCES

[1] Jung, M., ”Development of Omnidirectional Wheeled Mobile Robots Using Structural Properties”, *PhD Thesis*, Department of Electricial Engineering and Computer Science, KAIST, 2002.

[2] Siegwart, R. and Nourbakhsh I., ”Introduction to Autonomous Mobile Robots”, Massachusetts Institute of Technology, 2004.

[3] Campion, G. and Bastin, G. and Andrea-Novel, B., ”Structural Properties and Classification of Kinematic and Dynamic Models of Wheeled Mobile Robots”, *IEEE Transactions on Robotics and Automation*, Vol 12, No. 1, 1996.

[4] D.J. Stonier, R.J.Stonier, ”Obstacle Avoidance and Finite Time Tracking of Mobile Targets ”, *Proceedings of the 2nd International Conference on Autonomous Robots and Agents (ICARA)*, Editors S.C. Mukhopadhyay and G. Sen Gupta, Palmerston North, New Zealand, pp. 58-63, December 13-15, 2004.

[5] Sigal, L., Sclaroff, S., and Athitsos, V., ”Skin Color-Based Video Segmentation Under Time-Varying Illumination”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 26, 2004.

[6] Wu, Y., Liu, Q., and Huang, S., ”An Adaptive Self-Organizing Color Segmentation Algorithm with Application to Robust Real-time Human Hand Localization”, in *Proc. Asian Conf. on Computer Vision*, 2000.

[7] Kjeldsen, R. and Kender, J., ”Finding Skin in Color Image”, *Proc. of the 2nd International Conference on Automatic Face and Gesture Recognition(FG ’96)*, 1996.

[8] Morris, T. and Chauhan, v., ”Facial Feature Tacking for Cursor Control”, *Journal of Network and Computer Applications*, 2004.

[9] Soriano, M., Martinkauppi, B., Huovinen, S., and Laaksonen, M., ”Skin Detection in Video under Changing Illumination Conditions”, *In Proc. 15th International Conf. on Pattern Recognition, Vol 1*, 2000.

[10] Du, W., and Li, H., ”Vision Based Gesture Recognition System with Single Camera”, *5th International Conf. on Signal Processing Proceedings, Vol.2*, 2000.

[11] Kim, J.-H., Vadakkepat, P., ”Multi-Agent Systems:A Survey from the Robot-soccer Perspective”, *International Journalof Intelligent Automation and Soft Computing, Vol. 6:(1) pp.3-17*, 2000

[12] Yang, J.-M., Kim, J.-H., ”Sliding Mode Control for Trajectory Tracking of Nonholonomic Wheeled Mobile Robots”, *IEEE Transactions on Robotics and Automation, Vol. 15:3 pp.578-587*, 1999.

[13] Jung, M.-J., Jang, J.-S., Kim, J.-H., ”Development of Robosot Category Soccer Robots”, *Journal of Harbin Institute of Technology, Vol 8. (3) pp.300-302*, 2001.

[14] J.-H. Kim, Kim, K.-C., Kim, D.-H., Kim, Y.-J., Vadakkepat, P., ”Path Planning and Role Selectrion Mechanism for Soccer Robots”, *Proceesings of the 1998 IEEE International Conference on Robotics and Automation, Leuven, Belgium, pp. 3216-3221*, 1998.