Proceedings of the 2005 IEEE
International Conference on Mechatronics
July 10-12, 2005, Taipei, Taiwan

A New Hybrid System Architecture with Local Feedback Control of a Wheeled Mobile Manipulator

[1]Chih-Fu Chang, [1]Chun-Po Huang, [1,2]Li-Chen Fu, [1]Yu-Ming Yi, [1]Yu-Po Hsu,
[1]Dai-Jei Tzou, [2]Jerry Chen, [1]Joseph Lai and [1]I-Fan Lin

[1]*Department of Electrical Engineering*
[2]*Department of Computer Science and Information Engineering*
National Taiwan University, R.O.C.
e-mail: lichen@ccms.ntu.edu.tw

Abstract –In this paper, a novel hybrid system with a local feedback control architecture for a wheeled mobile manipulator (WMM) is proposed to seek a target and grasp it within an unknown indoor environment. The active behaviors of a WMM are able to explore environment, lock target, self-localization and avoid obstacles. Initially, an ingenious hybrid model which captures the continuous dynamics of the WMM and the event-driven collision-avoiding goal seeking process is established. Next, a two-level control architecture is devised for the WMM system, where the first level mainly handles sensor feedback subject to sensor fusion, whereas the second level is responsible for providing a well performed supervisory control that can manipulate all available surrounding resources to successfully accomplish the aforementioned mission. In the Advanced Control Lab of Dept. of Electrical Engineering at National Taiwan University, an actual WMM is developed, named The Treasure Hunter (TTH), which is able to hunt treasures in an unknown environment whereby the effectiveness of the proposed approach is satisfactorily demonstrated.

Keywords – Wheeled mobile manipulator, hybrid system, supervisory control

I. INTRODUCTION

The hybrid automataon has been studied extensively in recent years. There have been several topics in this field which remain attractive to lots of scholars, such as liveness, reachability, stability and controllability. For example, one of the important sub-topics on stability of discrete event system (DES) is concerning Lyapunov method [6] and output stability method [7]. Furthermore, Lyeros *et al.* developed a more general theory on dynamics property of a hybrid system [8]. Another is to use Linear Matrix Inequality (LMI) analysis to prove the stability property of hybrid systems [9]. From the viewpoint of system's structure, it is more complex to deal with such mobile robot or manipulator due to its excessive redundancy problem and somewhat intricate kinematics constraints, as revealed by [1],[2],[3].

The aim of this paper is to develop a hybrid system approach to realize a control architecture for a wheeled mobile manipulator (WMM) to execute a task of searching for a target and grasp it while wandering through the environment clustered with obstacle. This paper is organized as follows. The problem formulation and the pertaining system architecture of the WMM are presented in Section II and III, respectively. On the other hand, hybrid system modeling and control is introduced in Section IV. A visual tracking system is introduced in section V. The setup of the overall system and extensive simulation results are provided in Section VI, and finally conclusions are drawn in Section VII.

II. PROBLEM FORMULATION

The controller design of a highly complex system is very difficult to analysis with traditional methods so that it may take lots of time to adjust the resulting system parameters to yield better performance. On the other hand, all sub-systems may switch with optimal strategies, but the stability property may not be guaranteed if the initial state to the switched state can not locate inside the safety set of that state. To prevent this problem, a theoretical method for hybrid system is therefore needed to deal with such circumstance.

Consider a mobile manipulator built in The Advanced Control Lab of Dept. of Electrical Engineering at National Taiwan University, whose function is mainly designed for object searching and grasping. Here, the mobile base is assumed to be equipped with wheel encoders, ultra-sound sensors, a CCD camera, and a laser ranger finder. Its features include :

- novel mechanical design;
- exploring unknown environment;
- visual tracking system;
- 5 degrees of freedom (DOF) manipulator;
- remote control, power control, and supervisor system.

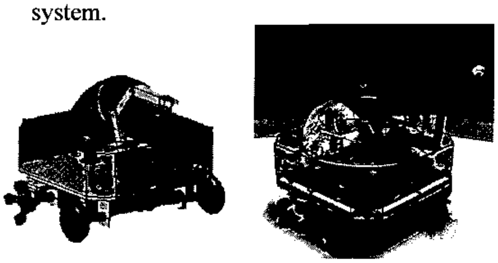


Figure 1,2 : The mobile manipulator named The Treasure Hunter (TTH) developed in NTU

Figure 3,4 : Innovative mechanical design and rotating wheel of TTH

III. SYSTEM ARCHETECTURE

As for the manipulator which is mounted on the mobile base, it is a 5DOF robot arm. Moreover, a DSP based ultrasonic sensing system with 6 ultrasonic sensors deployed to cover 6 different directions is adopted for collision avoidance. Later, this system will be fused with the signals from the DR system if the environmental information is going to be used to detect the robot's location.

Figure 5 shows the conceptual diagram of the system. There are two main processors embedded in the WMM which are used to process the main jobs, including calculation and I/O access. The first processor is TI DSP which is used to fuse the sensor signals and will be a backup system to take over the local motion control algorithm for reducing the system's computational loading. When PC104 is dedicated for running visual tracking algorithm, DSP will be assigned to cooperate with it.

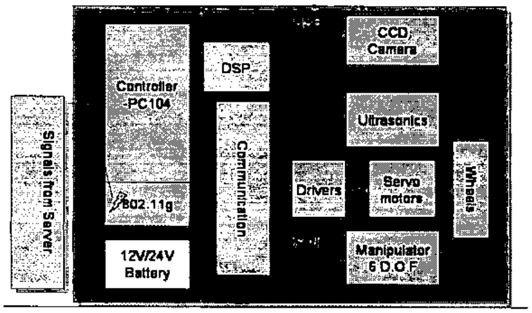


Figure 5 : System conceptual diagram

IV. HYBRID SYSTEM MODELING AND CONTROL

In this section, we start with the pertaining hybrid system model. After that, kinematics and dynamics model of the WMM, and its nonlinear controller design will be established with mathematic definitions.

4.1 Hybrid Automaton

A hybrid automaton is a dynamical system that describes the evolution in time of the valuations of a set of discrete and continuous variables. The stability analysis issues with dynamic property have been addressed in [6][7][8]. In this paper, a hybrid automata designed for WMM is implemented to evaluate the reachability and stability issue.

Definition 1. (Hybrid Automation) A hybrid automation H is a collection $H=(Q,X,U,Y,Init,f,Inv,E,G,R)$, where

- $Q=\{S,W,A,R_1,R_2,T_1,T_2,G,E\}\in R^9$: a finite set of discrete variables with the following meaning, S : "start", W : "wander", A : "approach", R_1, R_2 : "reverse", T_1, T_2 : "rough-tune" and "fine-tune", respectively, G : "grasp", and E : "end";;
- $X=\{v_v,w_v,\varepsilon_v,q_{m1},\dot{q}_{m1},\ldots,q_{m5},\dot{q}_{m5}\}\in R^{13}$: a finite set of continuous variables with $v_v\in R^2$ representing the linear velocity of the mobile manipulator, ε_v being the rotating angular velocity about the central axis of the mobile base, $(q_{mi},\dot{q}_{mi})$, $i=1\sim5$, being the joint displacement and velocity of the i-th joint of the manipulator;
- U : a set of input variables;
- $Y=\{v,s\}$: a set of output variables with v and s respectively denoting the visual measurement and the surrounding obstacle information (relative to WMM);
- $Init\subseteq Q\times X$: a set of initial states;
- $f:Q\times X\to X$: a vector field;
- $Inv:Q\to 2^X$: a domain (invariant set) under which the dynamics of the mobile manipulator hold;
- $E\subset Q\times Q$: a set of events;
- $G:E\to 2^X$: guard-set function;
- $R:E\times X\to 2^X$: reset relation.

Definition 2: An execution of a hybrid automation H is a collection $\chi=(\gamma,q,x)$, where γ is a hybrid time trajectory, $q\langle\gamma\rangle\to Q$ is a discrete variable, and $x=\{x^i;i\in\langle\gamma\rangle\}$ is a collection of dynamics such that

- $(q(0),x^0(0))\in Init$;
- $\dot{x}^i=f\left(q(i),x^i(t)\right)$ and $x^i(t)\in D\left(q(i)\right)\ \forall t\in[\gamma_i,\gamma'_i)$;
- $\forall i\in\langle\gamma\rangle\setminus\{N\}$, $e=\left(q(i),q(i+1)\right)\in E$,

$x^i(\tau'_i)\in G(e)$, and $x^{i+1}(\gamma_{i+1})\in R(e,x^i(\gamma'_i))$.

4.2 Supervisory Design

The hybrid system of WMM is actually composed of discrete and continuous parts. The conceptual diagram of the underlying hybrid automaton is depicted in Figure 8.

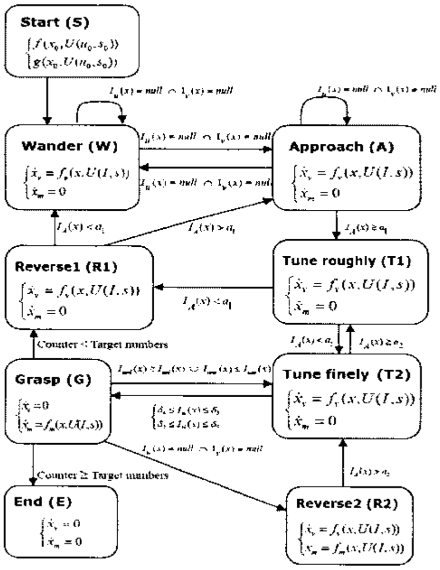
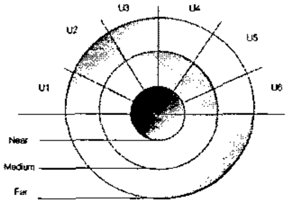


Figure 6 : The conceptual diagram of hybrid automaton

Note that $x = (x_v, x_m)$, where x_v and x_m respectively represent states of the mobile base and manipulator. As for the vector field, $f_v(\cdot,\cdot)$, it integrates the dynamics of the mobile base as well as the potential field force accounting for the determination of the input variable $U(I,s)$, which apparently relies on the measurements from both image sensor and the ultra-sound sensors. In contrast, the vector field $f_m(\cdot,\cdot)$ integrates the manipulator dynamics (or kinematics) and the image sensor measurement. Moreover, meaning of each state, namely, "start", "wander", "approach", "grasp", "reverse", "tune", and "end", is described below :

1. Start $S = \{True, False\}$: It means start of the mission;
2. Wander $W = \{True, False\}$: At this state, the WMM aims to move around within the indoor environment in a random walk manner while avoiding collision with obstacles. So far, there have been several ways to perform the random path planning and complexity of these algorithms at 2D environment has been studied [4]. The wandering with random walk strategy will explore the indoor environment completely as $\tau \to \infty$. In that case, the guard set G will be triggered eventually so that the state Approach will be reached, implying the visual contact of the target object will always be possible, namely, $I_u(x) \neq$ null and $I_v(x) \neq$ null, where $I_u(x)$ and $I_v(x)$ respectively refer to horizontal and vertical target detection in the CCD camera image.
3. Approach : At this state, the WMM will turn on the visual tracking mechanism so that the mobile robot will move towards the target object while trying to maintain visual contact with that object. However, if the area of the target in the image satisfies $I_A(x) > a_1$ for some appropriate value a_1, then the state will transfer from approach to rough-tune;
4. Rough-Tune $T_1 = \{True, False\}$: At this state, if the WMM drives close enough to the target object, *i.e.*, $I_A(x) > a_2$ for some appropriate a_2, then the state of rough-tune transfers to another state called fine-tune. Hereafter, the signal of laser range finder will be turned on until this fine-tune state is relieved;
5. Fine-Tune $T_2 = \{True, False\}$: When the laser point appears in some specific range of the image, which means the manipulator is at the right position for grasping, the robot will stop and enter the grasp state;
6. Grasp $G = \{True, False\}$: This state means that the manipulator will move to the grasping configuration and execute the grasp motion;
7. Reverse : Two reverse modes are established to deal with different situations.
   (1) "Reverse 1", $R_1 = \{True, False\}$: After failure to grasp the object, which is detected by CCD camera, or suffering from the loss of visual contact due to rough tuning, this state has to be executed immediately, i.e., the WMM will be backed away slightly to be ready again to access either the state rough-tune or the state grasp;
   (2) "Reverse 2", $R_2 = \{True, False\}$: After success of grasping one object and there is remaining mission to be completed, this state will be executed so that the WMM will be backed away significantly and the manipulator will get back to home configuration so that the wandering state will be accessed next.
8. End $E = \{True, False\}$: When all the grasping tasks are finished, the end state will be triggered.

From Figure 6, which shows logic flow among 9 states totally in the automaton, the hunting behavior starts with assigning all variables with initial value and transferring to the wander mode. At that time, the obstacle avoidance flag is set true to help the mobile manipulator navigating in the unknown environment. Here, we define $v = \{I_A, I_u, I_v\} \in R^3$. On the other hand, the discrete variable $s \in R^6$ depicts the distance message measured from the set of 6 ultra-sound sensors. Consequently, a major rule table is designed to avoid obstacles when the WMM searches through the environment the target object as illustrated in Figures 9,10.



Ultrasonic Distance	U1	U2	U3	U4	U5	U6
Near	LR	LR	B	B	SL	LL
Midium	SR	SR	A	A	SL	SL
Far	SR	SR	LA	LA	SL	SL

Figure 7,8 : The definition f ultrasonic working range and rule table for obstacle avoidance

In the rule table, LR denotes "Large Right" and SR is "Small Right" and B is "Reverse" and A is "Ahead" and LA is "Large Ahead" and SL is "Small Left" and LL is "Large Left".

Thus, the major processing flow of obstacle avoidance we formulate is as follows:

Step 1: Poll the signal from six ultra-sounds.

Step 2: Fusion signals with Fuzzy algorithm.

Step 3: Control the heading angle of the WMM.

The obstacle avoidance behavior is always true in the state of "W" until the state transmitting to another mode. In the state of "A", the behavior of obstacle avoidance will be activated by one of the six distances measured by ultra-sounds is short enough relative to our safe range.

4.3 Kinematics model of the WMM

The control variables of the WMM are composed of the linear speed w_{ave} of the mobile base and the angular velocity μ of its heading direction, namely :

$$w_{ave} = \frac{w_r + w_l}{2} \tag{1}$$

$$\mu = \frac{w_r - w_l}{w_r + w_l} \tag{2}$$

where w_r and w_l denote the rotating speeds of the right wheel and left wheel, respectively. Note that w_{ave} and μ can be used to control any movement of the mobile base. For example, the slow-speed dynamics of the base is expressed by

$$f_v(q_v) = \dot{q}_v = K_v J_v(q_v) u_v \tag{3}$$

with

$$\dot{q}_v = \begin{bmatrix} \dot{x}_v \\ \dot{y}_v \\ \dot{\phi}_v \\ \dot{\varepsilon}_v \end{bmatrix}, J_v(q_v) = \begin{bmatrix} \cos(\phi_v + \beta) & 0 & 0 \\ \sin(\phi_v + \beta) & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, u_v = \begin{bmatrix} r w_{ave} \\ \mu w_{ave} / b \\ \beta \end{bmatrix}$$

where ϕ_v denotes the heading angle of WMM, (x_v, y_v) is the position of WMM relative to a world coordinate origin, K_v stands for a positive constant.

According to Eq. (3), appropriate selections of w_{ave} and μ will result in the required motion for the vehicle. Given the values of w_{ave} and μ, the right and left wheel speeds of the mobile base can be obtained from

$$w_r = w_{ave}(1+\mu) \tag{4}$$

$$w_r = w_{ave}(1-\mu) \tag{5}$$

4.4 Kinematics model of a 5 DOF manipulator

There is a full set of researches on kinematics model of the manipulator [5]. The general form is expressed as

$$f_m(q_m) = \dot{q}_m = K_m J_m(q_m) u_m \tag{6}$$

where $\dot{q}_m = \begin{bmatrix} \dot{\theta}_1 & \cdots & \dot{\theta}_5 \end{bmatrix}^T$ with $\theta_i \in R, i = 1 \sim 5$ being the join variables of the manipulator, and meanings of J_m and u_m are straightforward and can be easily found, *e.g.*, in [14]. Also, we may find a nonlinear controller to control the manipulator subject to asymptotic stability property.

4.5 Dynamics model of WMM

The Lagrange formulation is used to establish equations of motion for the mobile manipulator [10],[14], which may lead to the following matrix form

$$M(x)\ddot{x} + V(x,\dot{x})\dot{x} + G(x) = E(x)\tau - A^T(x)\lambda \tag{7}$$

where $x = q_v \otimes q_m$, $M(x)$ is an inertia matrix, $V(x,\dot{x})$ is centripetal and Coriolis torques, $G(x)$ is a gravity term, $A(x)$ is a constraint matrix, and τ is a generalized control force (torque).

Given the dynamics of the mobile robot, as shown in Eq. (8), the following properties hold :

(a) $x^T\left(\dot{M}(x) - 2V(x,\dot{x})\right)x = 0$, $\forall x \in R^n$

(b) $\exists M_m, M_M$ s.t. $0 < M_m \le \|M(x)\| \le M_M < \infty$, $\forall x \in R^n$

(c) $\exists V_M$ s.t. $\|V(x,\dot{x})\| \le V_M \|x\|$, $\forall x \in R^n$

Proposition 1. (Local Nonlinear Controller Design)[10]
Consider the system described by (7) with the control law given by the solution τ of the following algebraic equation

$$\tau = E^+(x)(M\ddot{x}_d + V(x,\dot{x}_d)\dot{x}_d + G(x) + A^T(x)\lambda - K_p e - K_d \dot{e}) \tag{8}$$

with

$$e = x - x_d,\ \dot{x}_r = \dot{x}_d - \Lambda e,\ s = \dot{x} - \dot{x}_r = \dot{e} + \Lambda e$$

where $x_d \in R^n$, $\dot{x}_d \in R^n$ are respectively the desired position and velocity trajectories, $E^+(x) = \left(E(x)^T E(x)\right)^{-1} E(x)^T$ is a pseudo inverse matrix, and both K_p and K_d are positive definite diagonal matrices. Then, the system is shown to be exponentially stable.

Corollary 1: From Proposition 1, the desired velocity $\dot{x}_d$ is defined by Eqs. (3)(6) so that $\ddot{x}_d$ can be transformed to the following control space

$$\ddot{x}_d = K_2(\dot{J}(x_d)v_d + J(x_d)\dot{v}_d) \tag{9}$$

for appropriately defined $J(\cdot)$ and v_d. Then, the generalized control force (torque) defined as

$$\tau = E^+(x)(\overline{M}(x)\dot{v}_d + \overline{V}(x,v_d)v_d + G(x) + A^T\lambda - K_p e - K_d \dot{e}) \tag{10}$$

will ensure that the system is exponentially stable.

Proof : It is straightforward.

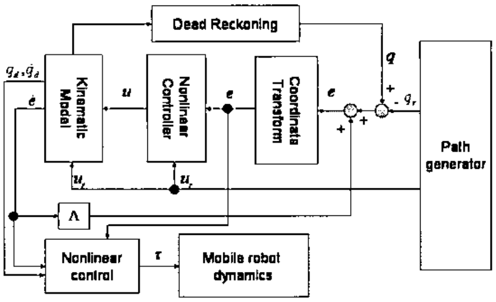


Figure 9 : Local nonlinear virtual torque control

Figure 9 displays the proposed control block. Actually, the implementation suffers from solving the inverse torque problem when we neglect the nonlinear actuator dynamics. In this case, the linear relationships between output velocity, torque and voltage are hereby assumed for simplicity of demonstrating the concept of this paper.

V. VISUAL TRACKING SYSTEM

The visual tracking system is divided into two subsystems – object detection and object tracking. After the Gaussian filtering, a template matching is used for object detection. When the object is detected successfully, another process is to deal with the object tracking. During this stage, the target object will be tracked after the image noises are removed through filtering and application of the so-called Hausdorff algorithm. That algorithm always compares the acquired image with the predefined template to find out the location of the potential target object.

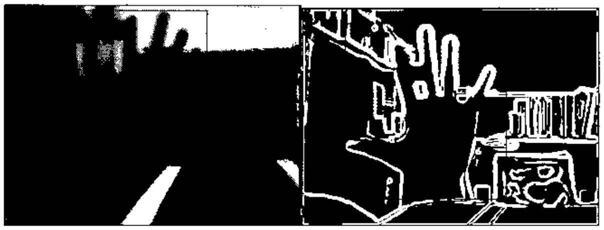


Figure 10,11 : Automatic searching for target silhouette with Hausdorff metric

VI. EXPERIMENT AND SIMULATION RESULTS

The experimental environment and devices are introduced first in the section. On the other hand, we would like to declare that the properties of the underlying hybrid automaton, including non-blocking, safety, and goal reaching, will hold through simulation. However, more theoretical study and justifications are currently under way.

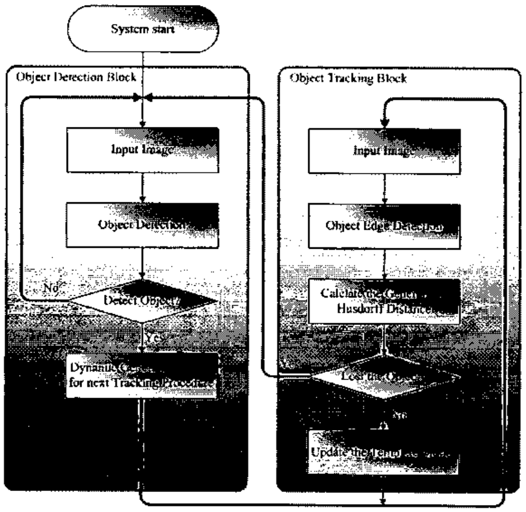


Figure 12 : The schematic of visual tracking system

6.1 Scenario and Task

As shown in Figure 13, the size of the room for the experiments is 4×5 meter^2. A tunnel consists of two corners and two targets is arranged in the room. The WMM developed in NTU, called TTH, starts to wander from the starting point (0,0,0) while turning on the collision avoidance mechanism. In this mode, the TTH will seek and lock the target in parallel with functioning of collision avoidance mechanism. When the TTH finds the target via CCD camera, it disables collision avoidance mechanism and go into tuning mode to approach to the target. During the tuning mode, the TTH tries to lock the target at the center of image. After approaching to the goal closely enough, the TTH starts to grasp the target slowly. After all targets are grasped successfully, we will conclude that the designated mission is fully accomplished.

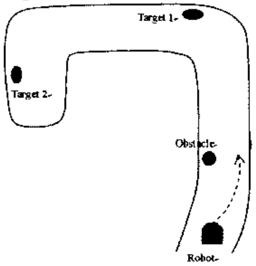


Figure 13 : Experiment scenario

6.2 Device Specification

Following the hybrid automaton, we design a mobile robot system with the hardware architecture as shown in Table.1. We set each device on the chassis made of aluminum sized by 450mm×450mm, and the height of this robot is 500mm.Our robot totally weights 11.2 Kilogram.

Table.1 : Hardware architecture

Device	Descriptions
Wireless LAN	3Com 802.11g USB Adapter
Ultrasonic Sensor	Polaroid × 6
Camera	Logitech QuickCam VGA CCD
Manipulator	Synax
Batteries	Yuasa 12V DC × 2
Main Computing System	Advantech Pentium III – 900Mhz PC/104 Module

All of functions of WMM such as collision avoidance, target searching and tracking, and object grasping are contributed by the integration of ultrasonic module, visual system, manipulator, and compute system. Moreover, the host computer dedicated to the reactive robot-vision surveillance, real-time model construction of the dynamic environment, and robot tele-operation in emergency via Wireless LAN. In the implementation of five kinds of states of this hybrid automaton, we set each state with different moving speeds as shown in Table.2.

Table.2 Moving speeds for different states

Mode	Velocity(cm/s)
Wandering	5~8
Approaching	5~8
Tuning Roughly	3~5
Tuning Finely	<1
Grasping	0
End	0

6.3 Simulation

Figure 14 : Simulation environment

Figure 15 shows the time history for state switching in treasure hunting game. Initially, the robot TTH wanders to explore the uncertain environment. Soon after that, the robot switches between two states, wandering state and reverse state, because it went to the corner, got restricted, and tried to escape.

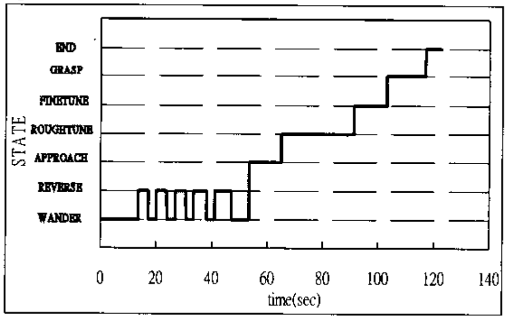


Figure 15 : An execution of hybrid automaton

When the TTH discovers any target, the wandering state will switch to the approach state. Following the supervisory control philosophy, it will then switch into rough-tune and fine-tune states in series. One can easily conclude that the grasping state will be reached in the figure, and the TTH grasp the target successfully at the end.

6.4 Experiment– Visual Tracking Mechanism

In order to find the area and centroid of the target, the method of signature analysis is applied. The signature, which is a projection, is the histogram of the nonzero pixels of the image. From the vertical and column projection, the area and centroid will be obtained. We denote the set of pixels in a target region by *R*. The global properties include the area of target I_A and the centroid (I_u, I_v) as defined below : Area: $I_A = \sum_{(r,c)\in R} 1$, and Centroid: $I_u = \frac{1}{I_A} \sum_{(r,c)\in R} r$, $I_v = \frac{1}{I_A} \sum_{(r,c)\in R} c$

For success to grasp the target, TTH has to maintain a fixed distance between itself and the target. A laser range finder equipped on THH is responsible for measuring the distance as mentioned above. In Figure 16, where a laser dot shown in the image starts to emerge when the blue target is tracked by TTH and is close enough to the robot, the location of the laser spot is at image coordinate (157, 105) whereas the calculation of the centroid of the blue target is located at image coordinate (48, 66.6). With this information, TTH knows how to steer itself to the right position for subsequent execution of grasp motion.

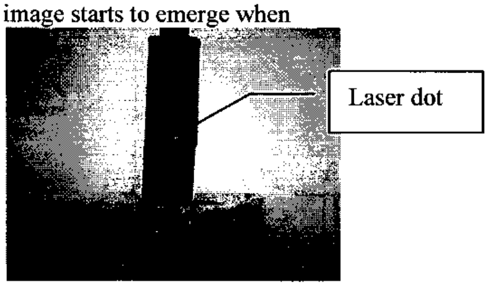
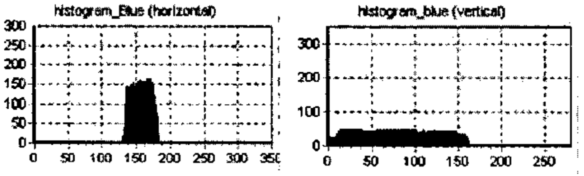


Figure 16 : Image capture by CCD camera.



Figures 17,18 : Horizontal and vertical projection of the blue target in the image plane.

In this experiment done at the Advanced Control Lab of Dept. of Electrical Engineering at National Taiwan University, TTH has demonstrated its superb capability in searching for two targets in an unknown indoor environment and successfully grasping the two target objects. The research team even won the 1st prize in the 1st International Student Hands-on Project Contest held in December 2004. The short video clip can be found on the website of the lab : http://acl.ee.ntu.edu.tw .

VII. CONCLUSIONS

In this paper, a novel hybrid system approach to design a control architecture for a WMM was proposed. The resulting capability facilitates WMM to search for a target and grasp it within an unknown indoor environment. Initially, a novel hybrid system model was developed which captures the continuous dynamics of the WMM and the event-driven collision-avoiding goal seeking process. Next, a two-level control architecture is devised for the WMM system, where the first level mainly handles sensor feedback subject to sensor fusion, whereas the second level is responsible for providing a well performed supervisory control that can manipulate all available surrounding resources to successfully accomplish the aforementioned mission. In the Advanced Control Lab of Dept. of Electrical Engineering at National Taiwan University (NTU), an actual WMM was built, named The Treasure Hunter (TTH), which is able to hunt treasures in an unknown environment. To demonstrate the effectiveness of the proposed approach, both simulation through Webots and experiment in NTU have been done and their results were provided or discussed.

REFERENCES

[1]Claudio Altafini, "Redundant Robotic Chains on Riemannian Submersions", *IEEE Trans. Robotics and Automation*,Vol. 20, No. 2,Apr. 2004

[2]M.H.Korayem,H.Ghariblu,"Maximum allowable load on wheeled mobile manipulators imposing redundancy constraints", *Robotics and Autonomous Systems*, Vol. 44, Page 151-159, 2003

[3]Zsolt Kemeny, "Redundancy Resolution in Robotics using Parameterization Though Null Space", *IEEE Trans. Industrial Electronics*, Vol. 50, No. 4, Aug 2003

[4] Marc Bui, Ajoy K. Datta and OliverFlauzac, "Randomized Adaptive Routing Based on Mobile Agents", *Proc. Computer Society*

[5] Jindong Tan and Ning Xi, "Unified Model Approach for Planning and Control of Mobile Manipulators", *Proc. IEEE International Conference on Robotics and Automation*, PP. 3145-3152, 2001

[6]Cuneyt M Ozvern and Alan S. Willsky, "Output Stabilizability of Discrete Event Dynamic Systems", *IEEE Trans. Automatic Control*, Vol. 36, No. 8, Aug. 1991

[7]Kevin M. Passino, Anthony N. Michel and Panos J. Antsaklis, "Lyapunov Stability of a Class of Discrete Event Systems", *IEEE Trans. Automatic Control*, Vol.39, No. 2, Feb. 1994

[8]John Lyeros, Karl Henrik Johansson, Slobodan N. Simic, Jun Zhang and S. Shankar Sastry, "Dynamical Properties of Hybrid Automata", *IEEE Trans. Automatic Control*, Vol. 48, No. 1, Jan. 2003

[9]Mingjun Zhang and Tzyh-Jong Tarn,"A Hybrid control Strategy for Nonlinear and Uderactuated Mechanical Systems", *IEEE Trans. Automatic Control*, Vol. 48, No. 10, Oct. 2003

[10]Chih-Fu Chang, Chin-I Huang and Li-Chen Fu, "Nonlinear Control of Wheeled Mobile Robot with Nonholonomic Constrain", *Proc. IEEE Conference Systems, Man, and Cybernetics*, 2004

[11]Raymond. A. Decarlo, Michael S.Branicky, Stefan Pettersson and Bengt Lennartson,"Perspectives and Results on the Stability and Stabilizability of Hybrid Systems", *Proc. IEEE*, Vol. 88, No. 7, July. 2000