Door opening control using the multi-fingered robotic hand for the indoor service robot PSR

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Abstract: In this paper, a practical methodology of hand-manipulator motion coordination for indoor service robot is introduced. This paper describes the procedures of opening door performed by service robot as a noticeable example of motion coordination. This paper presents well-structured framework for hand-manipulator motion coordination, which includes intelligent sensor data interpretation, object shape estimation, optimal grasping, on-line motion planning and behavior-based task execution. This proposed approach is focused on how to integrate the respective functions in harmony and enable the robot to complete its operation under the limitation of usable resources. As a practical example of implementation, the successful experimental results in opening door whose geometric parameters are unknown beforehand are provided.

Keywords: Service Robot, Coordinative Manipulation, Parameter Estimation, Opening a Door, Dextrous Robot Hand, Compliance Control

1. INTRODUCTION

Robots are entering recently towards applications beyond the structured and certain environment of a manufacturing industry. However, the current generation of service and field robots suffers major shortcomings because of their limited abilities for manipulation and interaction with humans. The development of robots in human environments will depend largely on the full integration of mobility and manipulation [8].

In KIST, a typical type of indoor service robot has developed a mobile platform and a 6 DOF robotic manipulator equipped with multi-fingered hand shown in Fig.1 [1,14]. Since those components have different mechanical characteristics in terms of motion scale, bandwidth, and design priorities, well-designed motion coordination strategy is essential in order to complete reliably its tasks even in an unstructured and unpredictable environment. In addition to the function of opening doors as mentioned above, service robot is supposed to have more functions to help people in such an complicated and dynamically changing environment.

There have been a few groups working for opening a door with mobile-manipulator system. The conventional approach to do the task is mainly dependent upon the ad hoc combination of position and force control. At a start, robot takes a tight hold of a knob by its hand and then tracks the pre-defined trajectory for opening door [2]. In order to protect the system against an undesirable high reaction forces at the fingertips caused by tracking errors, compliance control algorithm is applied in control strategy by implementing high-cost 6 axes force-torque sensor attached to the wrist of the manipulator [3,4,6,7,10] Slotine [5] proposed a simple method that follow the path of least resistance in order to open a door, turn a crank, and move a lever. Another door opening system has been presented, called ROMAN [6], but doubtfully, no information is provided how to open a door. Khatib [7,8] proposed effective dynamic behavior model regarded mobile-manipulator system as macro-micro manipulator. Petersson et al proposed on-line parameter estimation for target trajectory while mobile base move backward with drawing an arc. At this time, compliance control is applied to keep the pose of manipulator resolving the redundancy resolution [10]. Furthermore, the manipulator and the mobile base is controlled the simple automaton for opening door process, through the use of a hybrid dynamic system for discrete event control [11].

Fig. 1 KIST PSR1 for opening a door

In this research, a practical methodology of hand-manipulator motion coordination for indoor service robot is introduced. This paper describes the procedures of opening door performed by service robot as a noticeable example of motion coordination.

For these reasons, this paper presents well-structured framework for hand-manipulator motion coordination, which includes intelligent sensor data interpretation, object shape estimation, optimal grasping, on-line motion planning and behavior-based task execution.

This proposed approach is focused on how to integrate the respective functions in harmony and enable the robot to complete its operation under the limitation of usable resources. As a practical example of implementation, the successful experimental results in opening door whose geometric parameters are unknown beforehand are provided.

Section 2 explains the conceptual framework for the proposed door opening control using multi-fingered hand-arm for indoor service robot PSR1. In Section 3, a procedure of opening door is then introduced, followed by a description of each of task. The results of experiments are discussed in Section 4. Finally, some concluding remarks and future works are presented in Section 5.

2. MOTION COORDINATION BY HAND-ARM

The main issue of this research is motion coordination, which means that two or more mechanisms of different physical characteristics are integrated and controlled in accord to complete the common goals. Table 1 represents the functional categorization for those components. This concept is applied to hand-manipulator system of service robot where the hand has relatively small-scale motion and high-bandwidth property in terms of dynamics compared with the manipulator.

Table 1 Functional Categorization

	HAND	ARM	MOBILE
Function	Grasping	Manipulation	Moving
Workspace	10~20 cm	About 1.5 m	Unlimited
Stiffness	Low	Medium	Large
Inertia	A few g	About 20~30 kg	Over 100 kg
Accuracy	A few mm	Over 10 mm	A few ~ over 100 mm
Cycle time	A few msec	Over 10 msec	Over 100 msec

Therefore, motion coordination can be realized by attributing the operations requiring fast and small scale motion to hand and the other large-scale motions to manipulator, exchanging necessary information with each other. This is one aspect of the motion coordination, where the hand supplies serviceable pieces of information promptly to plan the manipulator trajectory.

2.1 The challenge approach by fingertip force

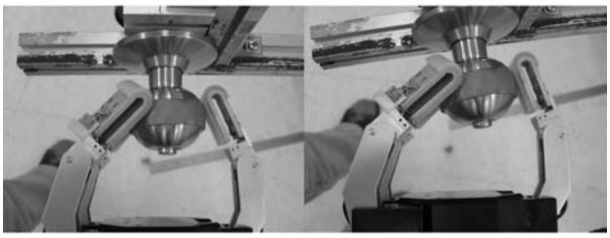
One of the competitive approaches in this research is that the low-priced strain-gage type force sensors [1] attached on the finger tips which are originally for the purpose of grasp force control can also replace efficiently and economically the expensive force-torque sensors in conventional approaches and be used to control compliance motion of the robot manipulator by combining kinematic information of hand. The final operation to complete door opening is to track the reference trajectory generated in previous on-line planning stage.

Another aspect of motion coordination can be found in this final step, where the shock of reaction forces due to manipulator tracking errors are compensated by applying high speed compliance control to the fingers.

2.2 Parameter Estimation by motion coordination

In this research, this section describes two parameter estimations: One of them is the center position of the doorknob for the stable grasping between the object and the multi-fingered hand. Other is the hinge position of the door for planning the trajectory of manipulator to open a door.

A multi-fingered robot hand grasps the doorknob after moving the front of the doorknob thorough the vision information on the wrist, and then parameter estimation is divided into two stages. First stage is to know the center position of the object by groping for an object. Second stage as shown in Fig. 2 is to know the door model by using the changed finger kinematic configuration while moving arbitrary the arm in order to open a door since the measurement by vision system has inherent errors.



(a) before (b) after

Fig. 2 Finger configuration changing after back and forth motion by arm

2.3 Petri net model for opening door

The whole processes in opening door are modeled through the technology of Petri-net based modeling, which is famous for its efficiency and extendability in discrete event system representation.

These approaches as mentioned above were embodied as a Petri-net model, integrated and implemented as a sub module in robot control program and experiment was made to prove that this methodology would guarantee the safety and robustness against an unexpected uncertainties in opening doors.

Fig. 3 and Table 2 represent the Petri net model of process *OpenDoor* in *low-level configuration*.

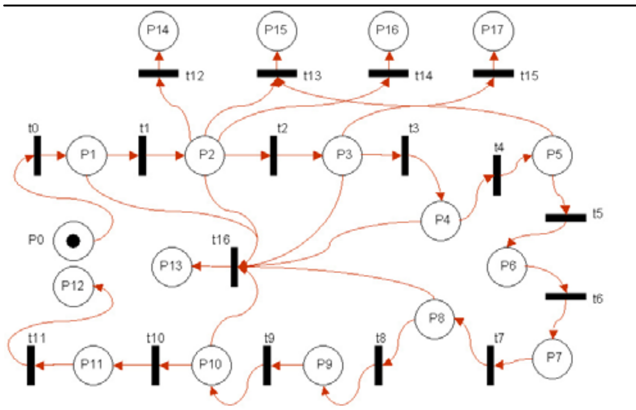


Fig. 3 Petri net model of process *OpenDoor* in *low-level configuration*

Table 2. Description of place and transitions of Fig. 2

PL/TR	Description
P_0	Standby
P_1	Execute behavior *BhMoveToTarget*
P_2	Execute behavior *BhMoveToSearch*
P_3	Execute behavior *BhMoveToTarget*
P_4	Execute behavior *BhMoveToOpenDoorPoint*
P_5	Execute behavior *BhObjectDetect*
P_6	Execute behavior *BhHandGraspObject*
P_7	Execute behavior *BhMoveToTarget*
P_8	Execute behavior *BhManiPullObject*
P_9	Execute behavior *BhHandReleaseObject*
P_{10}	Execute behavior *BhMoveToTarget*
P_{11}	Execute behavior *BhMoveToHome*
P_{12}	Complete the process ***CPrOpenDoor***
P_{13}	Fault : Target Position/Orientation of manipulator is out of workspace
P_{14}	Fault : Target object is out of reach. Process ***CPrMoveToGripPos*** should be generated to relocate the mobile at new position where the manipulator can reach the target object.
P_{15}	Fault : No Target object exists. Process ***CPrMoveToSrchPos*** should be generated to resume the search process at new position. If the search count exceed the limit, it would be concluded that the target object could not be detected.
P_{16}	Fault : vision system is malfunctioning.
P_{17}	Fault : Target object is out of sight
t_0	Start
t_1	Complete behavior *BhMoveToTarget*
t_2	Complete behavior *BhMoveToSearch*
t_3	Complete behavior *BhMoveToTarget*
t_4	Complete behavior *BhMoveToOpenDoorPoint*
t_5	Complete behavior *BhObjectDetect*
t_6	Complete behavior *BhHandGraspObject*
t_7	Complete behavior *BhMoveToTarget*
t_8	Complete behavior *BhManiPullObject*
t_9	Complete behavior *BhHandReleaseObject*
t_{10}	Complete behavior *BhMoveToTarget*
t_{11}	Complete behavior *BhMoveToHome*
t_{12}	Process ***CPrOpenDoor*** posts fault message "Target object is out of reach"
t_{13}	Process ***CPrOpenDoor*** posts fault message "Target object was not found"
t_{14}	Process ***CPrOpenDoor*** posts fault message "Vision system is not operating properly."
t_{15}	Process ***CPrOpenDoor*** posts fault message "Target object is out of sight"
t_{16}	Process ***CPrOpenDoor*** posts fault message "Target pos/ori is out of workspace."

3. OPENING DOOR PROCESS

The procedure of opening door proposed in this research is as follows, more detail description in literature on [15].

3.1 Vision tracking

At first, the robot finds the location of a door handle using CCD mono vision camera which is mounted on the wrist of the multi-fingered hand. But, measurement by vision system has inherent errors, which will provoke an unstable grasping posture.

3.2 Shape detection

Precise estimation of the doorknob location by touching the knob by fingers, then move to the desired wrist position. To overcome these problems, the robot estimates the shape of door handle by repeatedly touching the handle and measuring the fingertip forces and calculates the optimal grasping posture in accordance with the shape. Fig. 4 describes the result of Hough transform for detecting the doorknob repeatedly.

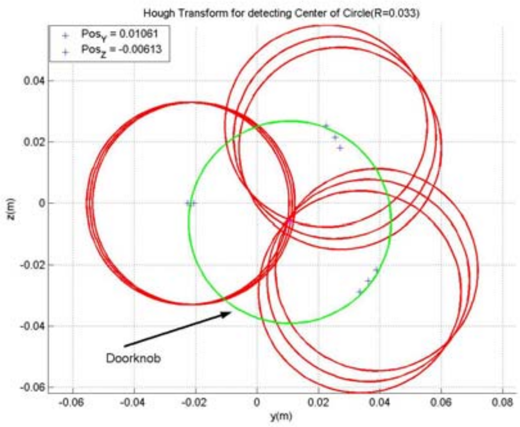


Fig. 4 Hough Transform for detecting Center of Circle (Radius of doorknob = 0.033 m)

3.3 Stable Grasping

After detecting the shape of the doorknob, the multi-finger hand should grasp stably the doorknob conditioned the constraint motion. It is a critical problem that the manipulator operates the planned trajectory while grasping the doorknob with multi-finger hand. In this research, stable grasping condition is in accord with the center position of the doorknob on that of the palm of the hand.

3.4 Pre-motion to find hinge point

Afterwards, it finds out the door parameters (ex. the position of door hinges relative to robot position. Another door parameters be assumed to be known previously and this assumption would be plausible in actual operation.) by measuring respective finger tip forces while shaking it slightly in arbitrary directions. From the estimated parameters, the manipulator trajectory for opening door is generated.

Assumptions:

1) The size and opening direction of door know.
2) Measurement by vision system has a relative orientation error. The range of angle offset is limited from –10 to 10 degree.
3) A contact point does not move on the object by the change in the relative orientation between the object and the fingertip.

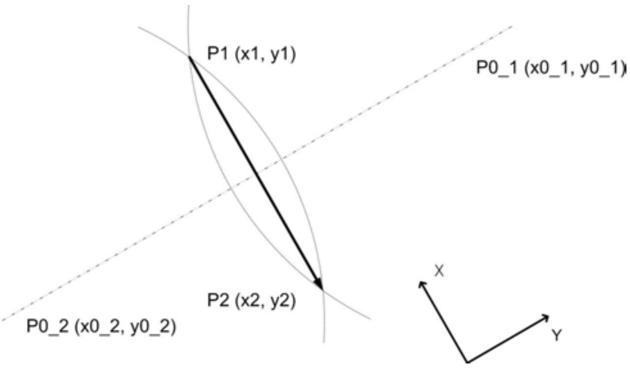


Fig. 5 Parameter estimation

Shake the hand slightly back-and-forth, and then estimate the trajectory of the knob. Circles making virtual hinge points both P0_1 and P0_2 have intersection position P1 and P2, shown in Fig. 5.

Equation (1) passing through from the point P1 to the point P2 is represented below.

$$2(x_2-x_1)x+2(y_2-y_1)y=x_2^2-x_1^2+y_2^2-y_1^2 \quad (1)$$

$$y=ax+b$$

where, $a=-\dfrac{x_2-x_1}{y_2-y_1}, b=\dfrac{x_2^2-x_1^2+y_2^2-y_1^2}{2(y_2-y_1)}$

Equation (1) and two equations of circle centered the virtual hinge points, P0_1 and P0_2, get a quadratic equation (2), which have the root meaning the hinge point of door.

$$(1+a^2)x^2+2(ab-x_1-ay_1)x+(b^2-2by_1+x_1^2+y_1^2-R^2)=0 \quad (2)$$

3.5 Contact force control by multi-fingered hand

The experiments for extracting the external forces and torques from the force sensors at the tips and for presuming the geometric configuration of the target object were performed, which produced the desirable results.

At first, External force on the wrist can be replaced using the fingertip force. It should be satisfied whether it is suitable only fingertip force sensors. Fig. 7 shows the experiment of fingertip force into external force.

To convert fingertip force to external force, grasp the doorknob rigidly. Then suspend a weight from 200 gram and 1800 gram from the doorknob. And the last rotate the robot hand on x-axis in 360 degree with about 20 degree intervals.

Equation (3) describes the projection of the fingertip force F_i onto y-z planes shown in Fig. 7.

$$f_i=F_i\cos a \quad (3)$$

where, i is finger number. F_i is the fingertip force.

Equation (4) decomposed the weight W into Fy and Fz.

$$\sum f_z=(f_{z1}+f_{z2}+f_{z3})=W\cos\alpha=-W_z$$
$$\sum f_y=(f_{y1}+f_{y2}+f_{y3})=W\sin\alpha=-W_y \quad (4)$$

where, $\alpha=ATAN\left(\dfrac{\sum f_y}{\sum f_z}\right)$

To prove the reliable external force or not, experiment of compliance carried out, shown in literature [15].

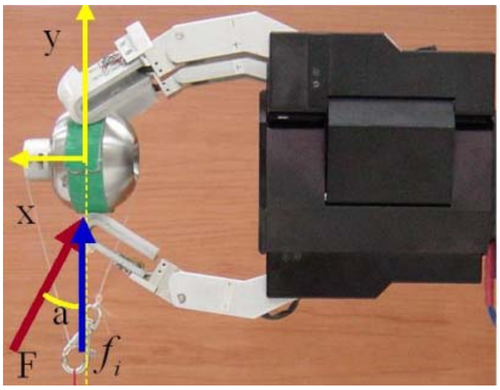


Fig. 7 Force equilibrium between fingertip force f and resultant force W

4. EXPERIMENTAL RESULTS

We implemented an open door process on target robot "Public Service Robot – PSR1" shown in Fig. 1. In this section, Experimental results compared the task with compliant control to not after finding out a kinematic parameter estimation of door are shown.

4.1 Kinematic parameter estimation

As mentioned in the previous chapter, opening door is mainly composed of two operation stages. In the first stage, service robot tries to find out the door parameters by synthesizing both the force data from each fingertip and geometric hand configuration changing as the manipulator is shaking the doorknob, where the hand-manipulator coordination plays a vital role in successful completion of the task.

In the following, robot plans the opening door trajectory based on the estimated parameters in the previous stage. While tracking the planned path, robot should make constant the gripping forces and simultaneously absorb the shock of the reaction forces at the fingertips caused by manipulation control errors.

4.2 Compliance control

To realize a compliant control, actually it is necessary the force sensor which is six degree of freedom type. However, our robot hand just has 2 degree of freedom forces data replacing fingertip forces into critical external force: y and z axis.

Fy and Fz convert to micro-movement by compliant matrix C, shown in equation (5). Then calculate inverse Jacobian matrix. Then each micro-movement of joint angles is calculated.

$$[\Delta\theta]_{6\times1} = [J]^{-1}_{6\times6} \begin{bmatrix} 0 & 0 & 0 & \\ 0 & c_1 & 0 & 0_{3\times3} \\ 0 & 0 & c_2 & \\ & 0_{3\times3} & & 0_{3\times3} \end{bmatrix} \begin{bmatrix} 0 \\ f_y \\ f_z \\ 0_{3\times1} \end{bmatrix} \quad (5)$$

where J is Jacobian of arm. C is compliant matrix.

4.3 Result

Total distance of opening was -0.03 m of x-axis, 0.010 m of y-axis, and about 25 degree, shown in Fig. 8. End-effector velocity of the manipulator was 0.002 m/sec. Sampling time was 300msec.

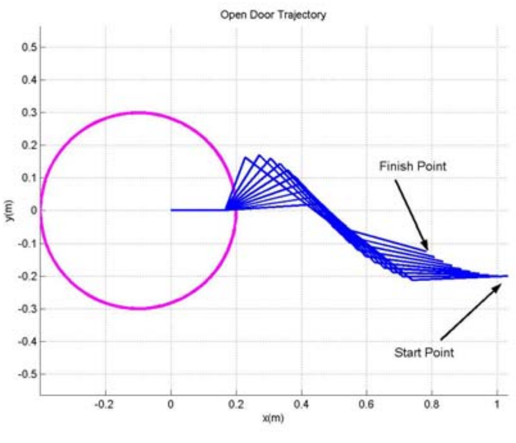


Fig. 8 Experiment result of trajectory

Here is another figure to describe. Fig. 9 shows the result of external force that compared to the task with compliant control or not. As may have been expected, it reported maximum external force about 5.2 N and average external force less than 1 N. Fig. 10 shows the result of joint trajectory compared the task with compliant motion or not. Proving the successful experiment result, challenge approach replacing fingertip force into external force was proved with view of the modest cost.

Without parameter estimation, several experiments showed the task failure for opening door process because of the mono vision camera error, mobile position error, and planned integrated joint error so on.

5. CONCLUSION

In this study, the conceptual framework for hand-manipulator motion coordination is introduced and proved to be much efficient and practical through the experimental verification. As a confirmatory example, the robot implemented with this motion coordination strategy has performed the door opening process successfully. In the process of development, it is showed that using low-cost force sensors mounted on the finger tips can enable the reliable estimation of the external forces and torques without high-cost force/torque sensors and this approach provides some guidelines of extracting core information from the limited resources and successfully utilizing them. The novel algorithm is proposed to figure out the geometric parameters of doors and on-line planned trajectory for opening. Moreover, this paper mentions about how to design and upgrade service robot control architecture using Petri-net based modeling and integrating technology. An efficient and intelligent unification of all these techniques not only makes it possible to open any types of doors in human environment, but also is expected to make an amazing breakthrough in service robot industry.

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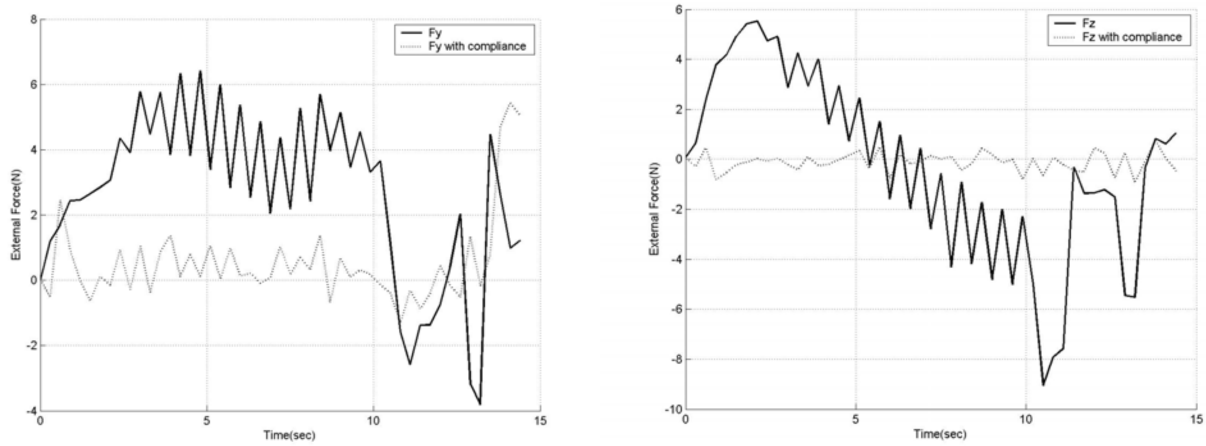

Fig. 9 The result of external forces compared compliant to position control

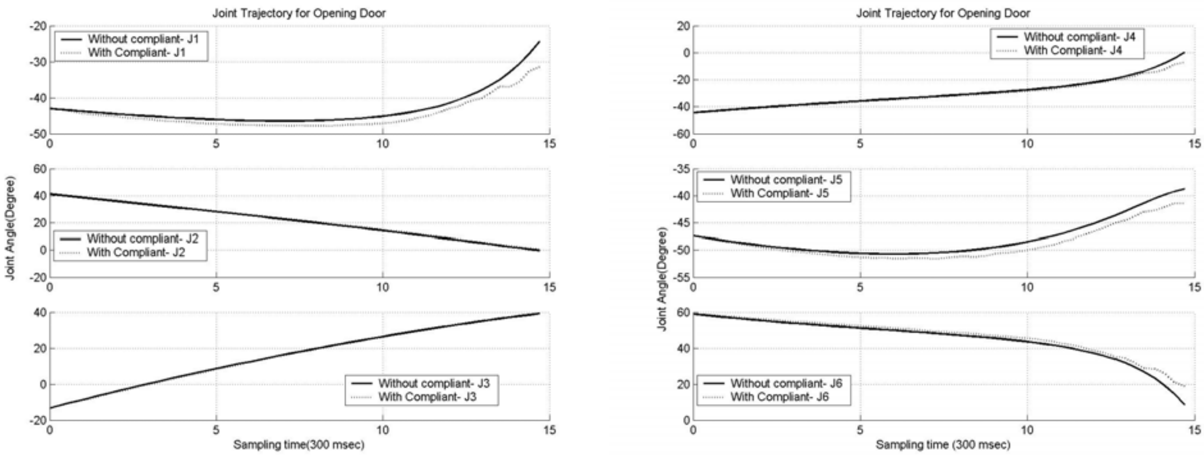

Fig. 10 The result of joint trajectory with compliant control

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