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Development of Modular and Reconfigurable Robot with Multiple Working Modes

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Abstract— **A modular and reconfigurable robot (MRR) with multiple working modes is developed for performing sophisticated tasks in uncontrolled environments. In the proposed MRR design, each joint module can independently work in active modes with position or torque control, or passive modes with friction compensation. Under a federated control system architecture, not only the MRR configuration can be reconfigured to adapt to various tasks, but also the working mode of each module, which can be switched on-line to satisfy the needs to carry out sophisticated tasks. Three joint modules have been developed, and the proposed method of passive working mode implementation with friction compensation has been tested experimentally. Door opening using a mobile manipulator consisting of the developed joint modules is studied as an application case study of the proposed multiple working mode MRR.**

I. Introduction

Robots are growing out of industrial plants into businesses and homes, fields and space, performing versatile tasks for service, security, rescue and space exploration among other areas of application. A mobile manipulator has many advantages over a fixed base manipulator either in terms of larger workspace or more dexterous manipulation capability. Such robots are required to have the abilities to carry out manipulations in uncontrolled environments, similarly as humans such as opening a door or even cooperative tasks with human beings.

In the mobile manipulator literature, attempts have been made to integrate traditional robot manipulators with mobile platforms. However, traditional robot manipulators are position controlled, with a fixed configuration and joints working in a single active mode. They have been very successful at manipulation in controlled environments such as a factory. However, when integrated with mobile robots, they substantially limit the application potential of mobile manipulators. Within controlled environments, the world can be adapted to the capabilities of the robot [1]. However, in uncontrolled environments, the robot has to adapt to the world consisting of only partially known or unknown objects and tasks, and real-time constraints. To date, there are still many challenges to develop robots for working in such uncontrolled environments or human environments [1]. A typical example is that, up to now, opening a door is still a difficult task for robots. For opening a general door, active mode is necessary for a robot manipulator to approach the door knob. After the gripper gets hold of the knob, some form of passive mode is desirable for the manipulator to follow the unknown door knob trajectory. On-line switching between position control and force control modes will be helpful during the door opening process. The present work is aimed to tackle such challenges by developing modular and reconfigurable robot manipulators capable of working in multiple modes and operating on mobile platforms. To this end, a modular and reconfigurable robot (MRR) consisting of modular rotary joints capable of multiple working modes has been developed and reported in this paper. With electronics embedded in the link modules, the developed joint modules are compact. Active and passive working modes have been implemented under a federated control system architecture that enables distributed module control with multiple working modes and centralized supervisory control.

A unique feature of our developed MRR robot joint is the implementation of both active and passive working modes on the same MRR modules. In the relevant literature, passive joints are used in the cooperation control of multiple manipulators [2-4]. In [3], the motion planning and control of mobile manipulators are greatly simplified with the introduction of exchangeable active/passive joints; the positioning error of the mobile manipulator can be absorbed passively and detected as the angular information of the passive joints. Relatively complex tasks are executed without the use of external sensors such as vision or a wrist force sensor.

Robot arms with passive impedance based on mechanical compliance have been investigated by many researchers. Design of robot joints with programmable passive impedance using antagonistic nonlinear springs and binary dampers was studied in [5]. Passive impedance control using viscoelastic material and a passive trunk mechanism was developed in [6]. A mechanical impedance adjuster was reported in [7] and [8], where a variable spring and damper adjusted by an electromagnetic brake were used for the passive compliant joint.

A recent hybrid joint was developed in [2], [9-10], which introduces an electromagnetic clutch between the motor and

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the output shaft. The hybrid joint has passive and active working modes. When the clutches are released, the joints are free and passively controlled by the coupling forces of the manipulator. The joint is capable of compliantly adapting to external force and motion by switching between the active and passive modes, depending on the requirement of a given task. The application of this hybrid joint needs a recovering algorithm to recover the measured joint position after the clutch was released and engaged again.

All of the above mentioned hybrid active/passive joints or passive mechanisms are specially designed, leading to extra weight and volume due to the additional components. In some cases, passive joints can help reduce power consumption, or increase flexibility, or guarantee safety in medical and service applications. It is desirable to be able to switch a normal robot joint to a passive operation mode without changing the existing joint mechanism or electronics system.

In our developed MRR, a simple and effective method to implement both active and passive operation modes and to switch between them is implemented, which is easy to apply in practice, without the need to change the mechanical structure of the joint. The proposed method involves joint friction compensation based on the motion trend of the joint. Three prototype modules have been developed in our laboratory and the design concepts have been validated.

The rest of the paper is organized as follows: Section 2 presents the mechanical and electronics design of the developed joint module. The proposed hybrid control system architecture and working mode switch are described in Section 3. The developed MRR modules are described in Section 4. Concluding remarks are given in Section 5.

II. Design of MRR Modules

A. MRR Joint Modules

A schematic diagram of the developed modular and reconfigurable robot joint modules is shown in Fig. 1, which consists of a brushless DC motor and drive, a harmonic drive with an integrated torque sensor and amplifier, an encoder, a brake, and homing and limit sensors [11]. The hardware architecture is shown in Fig. 2.

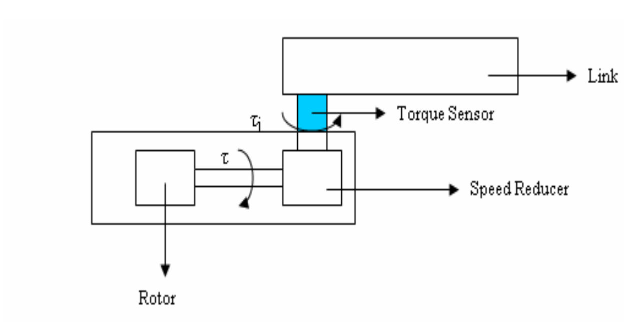

Fig. 1 Schematic diagram of an MRR module

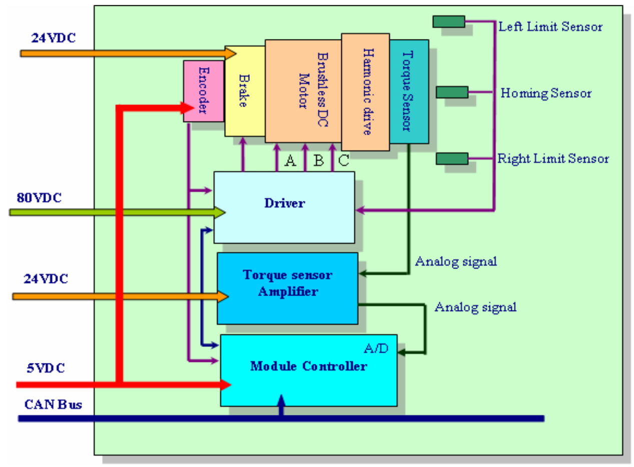

Fig. 2 Hardware architecture of an MRR module

Using a DSP based controller, the hardware architecture supports multiple control modes of the joint module including the basic torque (current) control mode and position control mode, as illustrated in Fig. 3.

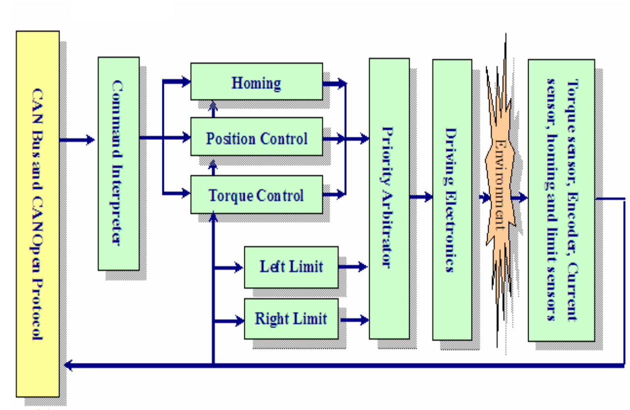

Fig. 3 Control system architecture of an MRR module

There are several layers in this architecture. The first layer, communication layer, is realized by the CAN Bus and its protocol. The decision layer is a command interpreter which decodes the commands according to the communication protocol and then determines the working mode and task to perform, such as homing, position control, torque control or passive mode control to be explained in the following section. The action layer includes various tasks such as calibrating, homing, and determining limits.

In the motor drive, the homing and limiting procedures are the pre-programmed sub-routines and have pre-set priorities, and what the users need to do is to activate these functions. The drive electronics in the execution layer outputs power signals (PWM) to drive the motor. The sensing layer includes torque sensor, encoder, current sensor, homing and limit sensors and their amplifiers or signal conditioning circuits. These sensors provide feedback to the module controller, and also to the supervisor controller through the communication layer for on-line planning.

Two types of joint modules have been developed recently in our laboratory using the TMS320F2812 DSP controller. As shown in Figs. 4(a) & (b), two compact modules are assembled, with electronics embedded in the tube link. It can be reconfigured at the interface between the joint and link. A relatively large module of a different type has also been developed, which has two interfaces with power and communication connectors to connect to the base support for reconfiguration. An assembled three module configuration is shown in Fig. 5.

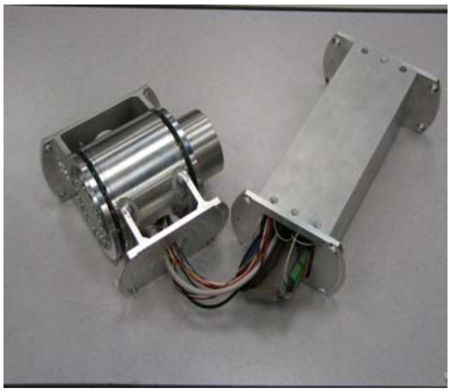

Fig. 4(a) One MRR module

Fig. 4(b) Two MRR modules

Fig. 5 MRR with three modules

B. Control System Architecture of MRR

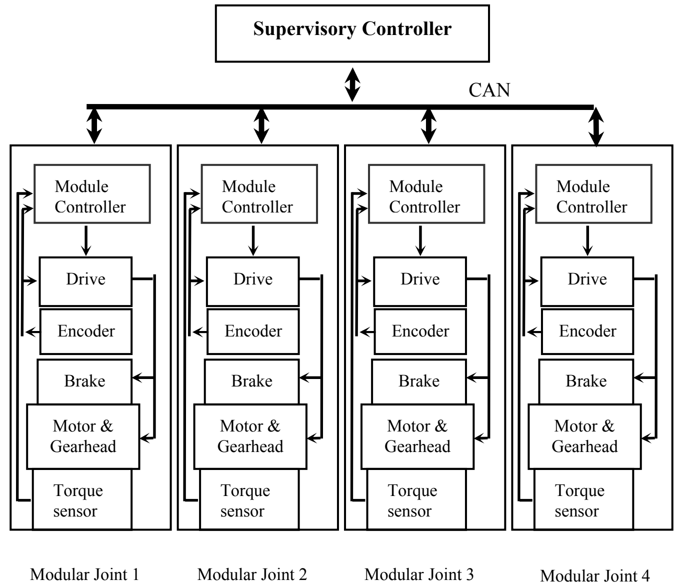

Fig. 6 Control system architecture of MRR

The overall MRR control system architecture is shown in Fig. 6. The architecture is the overall organization of the MRR control system, specifically the inter-relatedness of components within the system. It determines the execution sequence of the individual components and defines the flow of information among them. Traditional robot control system architectures are centralized, usually with a single processor managing all the computations and controls all robot components. One major merit of a centralized control system is that it is easier to achieve a global optimal solution for some tasks than other architectures, such as coordinated control and global trajectory planning. However, for a modular and re-configurable robot, the module control tasks, including module's position control, torque/force control, friction compensation, homing, limit detection and control, should be distributed to the module in order to achieve modularity and satisfy the self-contained requirement [12]. However, not all of the tasks of an MRR manipulator can be distributed to the module controller, and centralized processing is essential for tasks such as on-line trajectory planning, task space control, and coordinating control of multiple modular joints. The working mode of each module is determined by the supervisory controller as required to carry out particular tasks, which is transmitted through the CAN bus and interpreted by the command interpreter at each module. The proposed federated architecture shown in Fig. 6 has been developed to serve all the purposes [11].

III. PASSIVE MODE CONTROL

In this section, a proposed method to implement passive mode control of an MRR joint with friction compensation based on motion trend is presented. The motion trend of a robot joint is normally known or predictable. For instance, when a mobile manipulator is to open a door, the direction of the door's movement is known, and the motion trend of the robot can be predicted. Based on the motion trend of each passive joint, a feedforward torque is applied to compensate the friction at the joint, which is the key to implement passive operation mode of the joint without introducing extra mechanisms. If friction is compensated, the output shaft of the joint can be moved freely and work in a passive mode. The proposed method does not need a clutch to separate the output shaft from the motor and gear. Also, as the actuation chain is never disconnected, the joint can be switched back to an active working mode any time at any position without the need to recover from a disconnection.

A. Friction Model and Compensation

In the friction modeling and compensation literature, there have been many friction models reported [13]. The following two are well known simple friction models. The curves in Fig. 7 show the two friction models graphically.

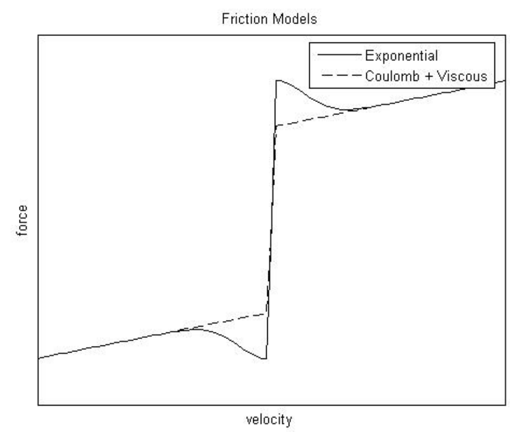

Fig. 7 Plots of two friction models

1) Coulomb and Viscous Model

A Coulomb and viscous model can be expressed as:

$$F\left(\dot{q}\right)=\left[f_c \operatorname{sgn}\left(\dot{q}\right)+b\dot{q}\right] \tag{1}$$

where F is the friction force, $\dot{q}$ is the relative velocity of the contact surfaces, b is the viscous friction coefficient, and f_C is the Coulomb friction. The sign function is defined as:

$$\operatorname{sgn}\left(\dot{q}\right)=\begin{cases}1 & for \quad \dot{q}>0\\ 0 & for \quad \dot{q}=0\\ -1 & for \quad \dot{q}<0\end{cases} \tag{2}$$

2) Static and Stribeck Model

The model in equation (1) does not accurately reflect what takes place at low speeds in real systems. It is known that when two objects are in contact, it takes an initial force to push them apart. This force is often referred to as the break away force and the phenomenon is described as static friction or “stiction”. What follows is a nonlinear region between the break away force and the viscous friction. This region is referred to as the Stribeck region. The following model describes this behavior:

$$F(\dot{q})=\left[f_c+(f_s-f_c)e^{-\left|\frac{\dot{q}}{f_\tau}\right|^{\delta}}\right]\operatorname{sgn}(\dot{q})+b\dot{q} \tag{3}$$

where $f\tau$ and fs are the Stribeck coefficient and the static friction coefficient, respectively [13].

3) Friction Compensation

Friction compensation has been extensively investigated for robot joints working in active control modes. Model uncertainty and nonlinear characteristics of friction are crucial issues in high precision motion control, especially at lower speeds [14-17]. The nominal friction model parameters are often assumed known or identified [18].

For the proposed implementation of passive joint operation, the requirement for friction compensation is fundamentally different from that for precise tracking control. In order for the joint to work in a passive mode, the joint friction only needs to be compensated such that the external torque can rotate the joint. In other words, the uncompensated friction should be much smaller compared to the magnitude of the external torque.

As shown in Fig. 8, friction can be separated into two parts: a constant part and a variable part, and the magnitude of the constant friction part often dominates the overall magnitude of the total friction at lower speeds. The constant part of friction, *fm,* is less than the static friction f_s and has the same sign as f_s. The sign is determined by the trend of the relative movement. In many situations, the trend can be predicted by kinematics analysis or measured by a toque sensor. For example, when a manipulator is used to open a door, after the gripper holds the door knob, the moving direction of the door is known, and the trend of motion of the robot joints can be predicted.

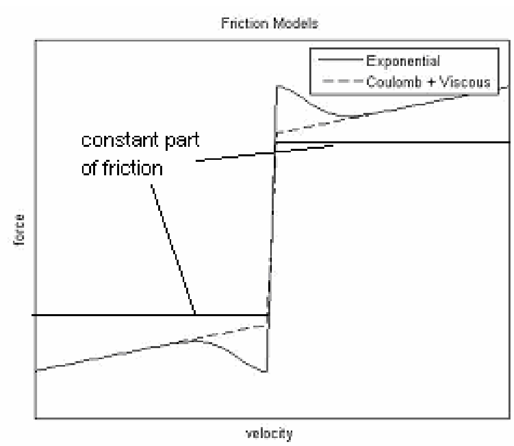

Fig. 8 Constant part of friction

After compensating the constant part, the friction models (1) and (3) become

$$\Delta F(\dot{q}) = F(\dot{q}) - f_m \operatorname{sgn}(\dot{q})$$
$$= (f_c - f_m)\operatorname{sgn}(\dot{q}) + b\dot{q} \quad (4)$$

and

$$\Delta F(\dot{q}) = F(\dot{q}) - f_m \operatorname{sgn}(\dot{q})$$
$$= \left[(f_c - f_m) + (f_s - f_c) e^{-\left|\frac{\dot{q}}{f_\tau}\right|^{\delta}} \right] \operatorname{sgn}(\dot{q}) + b\dot{q} \quad (5)$$

respectively, as shown in Fig. 9.

The compensation of the constant friction part is achieved by setting the module to torque control mode and sending a constant current command to the motor drive based on the motion trend of the joint.

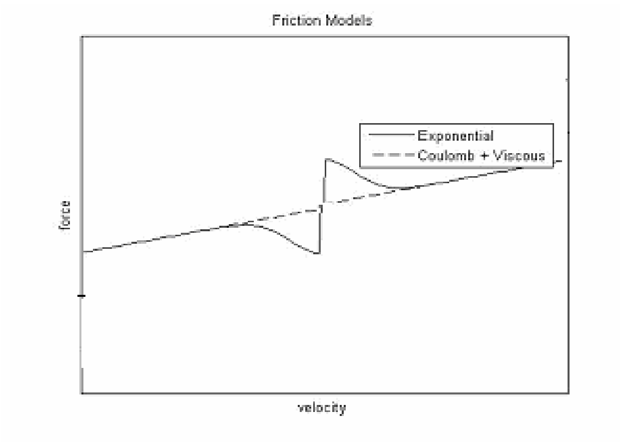

Fig. 9 Friction after compensation of the constant part

B. *Experimental Validation*

The concept of passive working mode implementation with friction compensation has been tested experimentally using the base module shown in Fig. 5. The currents for compensation are: -1.5 A for the positive direction and +1.2 A for the negative direction. With and without friction compensation, the external torques required to rotate the MRR joint in the passive mode in two different directions are measured and given in Table I.

Table I External Torque for MRR Joint in Passive Mode

Rotate Direction	**Positive** (0~360 deg)	**Negative** (0 ~ -360 deg)
Torque without compensation(a)	36.3 Nm	36.2 Nm
Torque with compensation(b)	7.6 Nm	5.7 Nm
Ratio (b/a)	21 %	16 %

From Table I, with the simple friction compensation, the required external torque to rotate the joint has been greatly reduced, by 79% in the positive direction and 84% in the negative direction. Such results have been adequate for many applications. Friction compensation using a more complete friction model or the torque sensor feedback can reduce the friction further if necessary.

IV. Door Opening Application Case Study

As an application case study of the proposed multiple working mode robot control approach, door opening using passive working mode is studied, which has been a challenging task so far for mobile manipulators [19-20].

Fig. 10 shows a planar model of the door opening process. The door opening motion is assumed to be planar and follow an arc trajectory in the x-y plane with a centre of rotation at (x_0, y_0) and a radius r. Assume that the gripper holds the door handle or knob firmly, and the handle position (x, y) during the door opening process forms the gripper's trajectory. The following relation has to hold:

$$r^2 = (x - x_0)^2 + (y - y_0)^2 \quad (5)$$

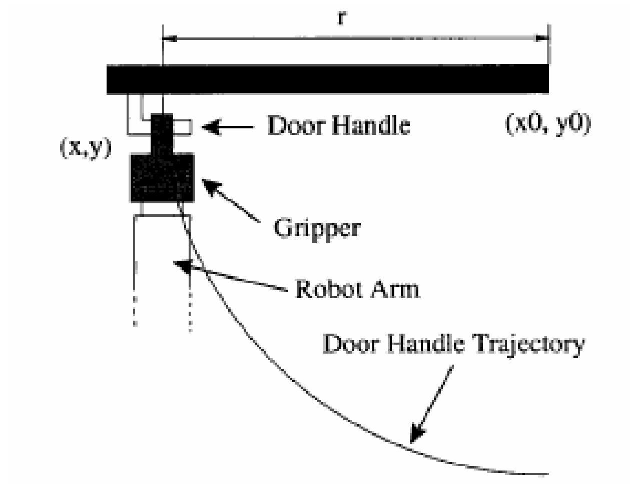

Fig. 10 A planar model of door opening

With only active working mode, the mobile platform needs to move continually in the whole door opening process while all joints of the manipulator are under active control. The disadvantages associated with such a door opening approach include: 1) complicated control techniques such as compliant motion control and predictive control are required [19]; 2) a precise path or motion planning is required for the mobile platform and all joints of the manipulator, which involves accurate kinematics models and solving complex matrix equations [20]; and 3) the door parameters such as the rotation center and the distance between the pivot and the knob have to be estimated on-line.

Fig. 11 illustrates the process of opening a door using a three joints planar manipulator. After the gripper opens the door lock, the second joint and the third joint are switched to passive mode, and only the first joint is still in active mode and under position control. In Fig. 11, the three links are assumed rigid. As assumed, the gripper has held the door handle or knob firmly. At this point, Joint 1 remains in an active control mode, but Joints 2 and 3 are switched to passive mode. After Joint 1 moves to θ_1', the two passive joints will rotate to θ_2' and θ_3', respectively, due to external torques. The door is rotated to the OA' position from the initial OA position.

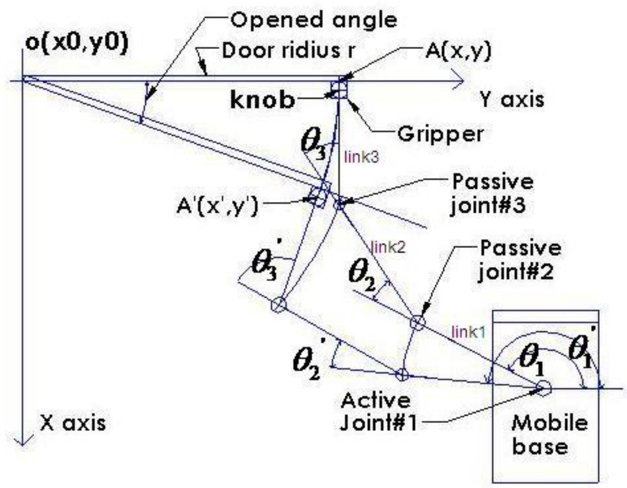

Fig. 11 Door opening procedure with two passive joints and one active joint.

During this process, only the trend of the door's rotation is known to the robot controller. After the door is opened to a certain angle, the mobile platform moves to next position, and the manipulator repeats the above process until the door is fully opened. The path planning for the mobile platform is greatly simplified as there is no need for a continuous path. The mobile platform needs only to stop at a proper area (not a point), which is similar to what human being does.

From this simple case study, we can see that mobile manipulators with the proposed multiple mode control create behaviors closer to those of human being, leading to substantial improvement in abilities to adapt to complicated human environments.

V. CONCLUSION

This paper presents the development of MRR modules with multiple working modes. Based on a proposed control system architecture, a simple and effective method for switching a joint module between active and passive modes is put forward. A unique way to implement passive working mode is developed by compensating static friction using the motion trend of the joint. The active / passive mode switch is implemented by software, without involving mechanisms such as a clutch. System reconfiguration becomes simple and more reliable.

Three joint modules have been developed, and the preliminary experimental results have shown the effectiveness of the proposed MRR control approach. Door opening using a mobile manipulator consisting of the developed joint modules has been studied as an application case study.

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