On the Development of a Quick Connect Disconnect Coupler for Rapidly Configured Modular Robots

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Abstract

In this paper, we present a novel modular robot connection that provides for the rapid deployment of automation through the quick and rapid configuration of robotic devices based on modules. Modular robots have certain advantages over conventional robots. A modular robot, can be defined as one for which the interchange of link and joint modules quickly occurs with minimal basic adaptations to the base robotic hardware, eliminates many of the flexibility constraints of current robots and re-uses the modules for future configurations. One important component of a modular robot is a Quick Connect/Disconnect (QCD) joint coupler which provides for connection and separation as well as orientation of the individual link-joint-actuator modules.

QCD based robots find applications in pilot and prototyping environments, in manufacturing lines with low volume and multi-product production, and on mobile platforms for unstructured manufacturing scenarios such as hazardous material handling and other manufacturing environments.

1. Introduction

Competitiveness and survival of manufacturing industries depends on the ability to introduce products in the market in a timely manner. In doing so, companies must have the means for the rapid deployment of automation tools, especially in the factory floor, and the ability to quickly reconfigure and maintain their automation tools, both software and hardware.

A modular robot connection addresses problems and difficulties associated with the reconfiguration and maintenance of modular robotic devices. The Quick Connect Disconnect (QCD) coupler, on which this work is based, provides for the quick and rapid configuration of robotic devices based on modules. A module is defined as a self contained electromechanical entity consisting of link-joint-actuator elements.

The QCD, as discussed in this work, performs various functions, and one of its important features is that it can be actuated remotely and be *robot friendly*, thus allowing connection without the need for physical human intervention. The hardware will provide the means for quickly configuring a robotic manipulator of various configurations using the available modules. An important part of this manipulator set is a connector that provides the mechanical requirements for quickly connecting the various hardware modules together and meets the electrical requirements for power and information transfer. The male and female components of this connector are shown in Figure 1.

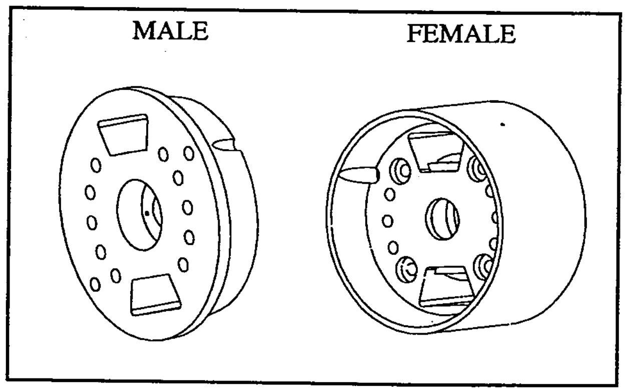

Figure 1: Male and Female Components of the QCD Coupler

A modular robot, can be defined as one for which the interchange of link and joint modules quickly occurs with minimal basic adaptations to the robotic hardware and eliminates many of the flexibility constraints of current robots. Modular robots have certain advantages over conventional robots. Conventional robots are monolithic; normally they are limited in configuration alternatives, in controllability, and in the ability to update and easily maintain hardware components. Conventional robots are associated with extensive setup and downtime for repairs,

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manufacturing space, and capital expenditures not only for equipment but for personnel training, as personnel must be versatile in a multitude of programming languages as well.

Another major disdvantage of conventional monolithic robots is that their components can not be replaced with new state of the art technology as this technology becomes available. Therefore, with reference to technology advancements, conventional robots have the disdvantage of becoming obsolete.

In theory, a robot utilizing modular, interchangeable and variously sized links and actuators, and employing modular and open architecture control software could be configured quickly either as articulated, SCARA or other configuration depending on the application. The generic module idea and two candidate geometrical configurations, articulate and SCARA, are shown in Figure 2 and Figure 3 respectively.

In this paper, a brief overview of the modular robotic research relating to actual implementation is given. Existing industrial end-of-arm tool changing devices/designs and their limitations for modular robotic implementation are then discussed. The design of a QCD concept is presented, followed by experimental results on the performance of the manufactured QCD.

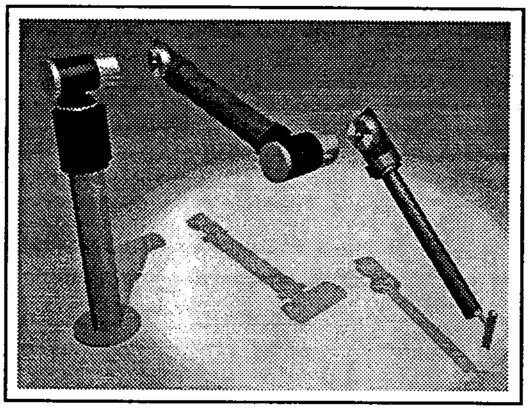

Figure 2: Expanded View of QCD Based Modular Articulated Configuration

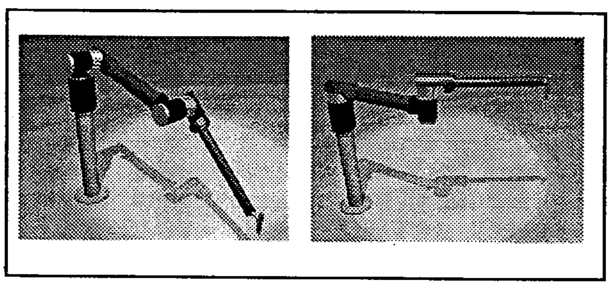

Figure 3: QCD Based Modular Articulate and SCARA Configurations

2. Background of Modular Robotics

The concept of a reconfigurable modular robot is not a new one. Academic research on modular robots have been performed for the last decade. This research addressed the area of hardware and development of methodologies for module selection. Industrial research relating to modular robots has been addressed through the development of linear actuators which are bolted together to develop cantilevered gantry type mechanisms.

In the academic hardware realm, the emphasis was placed on the definition of a module and its characteristics. Robotic systems such as the "Modular Robot System" from the University of Stuttgart [Wurst, 1986] and the "RMMS-Reconfigurable Modular Manipulator System" at Carnegie Mellon University [Schmitz, 1988] have been presented. Further steps in defining modular systems were undertaken at the University of Texas at Austin [Tesar, 1989], the Science University of Tokyo [Fukuda, 1988; 1989], the Nagoya University, Japan [Fukuda, 1991] and the University of Toronto [Cohen, 1992]. These designs proved that a total system can be configured for various tasks with minimal modifications.

However, there was little or no mention of the physical characteristics or the design of the part of the module that will provide the means for rapidly configuring a robotic device.

3. QCD Design

The design and definition of a modular system has been studied extensively. The characteristics of the connection between the modules remains relatively unexplored and inconsistent among the various researchers. Most modular system studies only address the theoretical application of modularity without discussing the practicality of operation. When connection is addressed, most of the previously mentioned researchers designed manually bolted connections for the modules. These connections are classified as *human friendly connections*. Although bolting is inexpensive, it can not be classified as a quick connection. Furthermore, bolting requires extensive human intervention as well as considerable down-time in order to perform the connection.

Cohen developed a connection mechanism that allows for 90° relative indexing [Cohen, 1992]. This mechanism is defined as a semi-quick-connect connection which cannot be classified as a module that provides either rapid or automatic connection of the modules. In Cohen's work there is no discussion about provisions for electrical or fluid connections through the connection, thus requiring extensive human intervention to perform them between the modules. Cohen did not discuss the actual physical characteristics of the modules (links, mechanical and elec-

However, he attempted a performance comparison with a PUMA 562 robot. A comparison between our modular robot (QCDBot for QCD Based Robot), Cohen's modular robot and the non-modular PUMA 562 is presented in Section 5.

Fukuda developed an automatic connection as one of the early QCD's [Fukuda, 1988; 1989; 1991]. Although innovative in concept by employing shape memory alloy springs, the modules rest on a two dimensional surface. However, specific advances in the design to acquire a three dimensional operation mode were not given, and further results have not appeared. The design also lacked automated electrical or fluid connections between the cells. Fukuda did not discuss actual physical characteristics of the modules such as payload capacity, actuator selection, etc. Therefore, no comparison can be performed between this and other concepts.

The need for modular robot components has been addressed in industrial applications with the development of end-of-arm tool changing devices which meet criteria similar to those defined in our work. Companies, such as PhD Robotics, Assurance Technologies, Applied Robotics, and EOA, have been producing retooling end effector devices for the past decade [PhD Robotics, 1993; Assurance Technologies, 1994; EOA, 1994]. Although these end effector devices vary in design, each can provide fluid and electrical line connections similar to our needs. However, none of these companies develop their devices with the intent to modularize more than the end effector. This is apparent in the size of the connectors, the smaller load bearing capacities, in both total capacity and type of loading, and the number and placement of fluid and electrical lines.

4. QCD Characteristics and Components

The QCD, as discussed here, performs the following basic functions. The first QCD function includes quick coupling and decoupling for the modules. Second, the QCD can simultaneously provide a connection interface for information and power transfer from the robot base out to the end effector. Each module can accommodate the connections for any potential configuration. Finally, the physical mating connection can actuate remotely and be *robot friendly*, thus allowing connection without the need for physical human intervention. The actuating power for the coupling and decoupling mechanism of the current QCD requires the application of *50 psi* air pressure.

The various components of the QCD are the mating surfaces, the locking mechanism, the electrical lines (information and power) and the fluid lines. The functions of these components, and the reason for their design will be briefly discussed.

4.1. Mating Surface

The first consideration was the mating surface. Because of the need to pass through fluid and electrical lines from the base of the robot to the end effector, the QCD would require considerably more connections than the average end effector tool changer device. This required that the mating surface be large enough to accommodate these lines.

Most end effector devices employ a flat mating surface. Although this is simple to operate and manufacture, a more complex mating surface could provide better force transfer and higher accuracies in mating and repeatability, Figure 4. We chose to employ a flat surface in the interior of the QCD that provides the optimum geometry for proper electrical and fluid line connections. However, a conical surface that encompasses a small part of the outer diameter of the QCD provides many mating advantages such as smaller indexing and coupling forces, automatic alignment between the two parts (this improves accuracy once in the final position much like an interference connection) and the indexing devices are placed in the conical surface area (this allows for larger rotational resistance due to the increased moment arm).

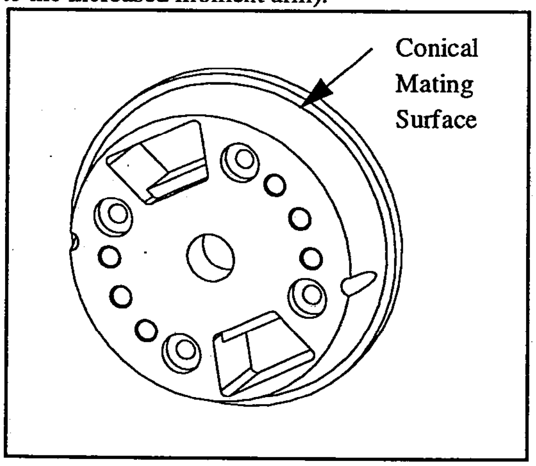

Figure 4: QCD Coupler Mating Surface

4.2. Mechanical Locking Device

Although many locking techniques are available, we use a male collared stem and a pneumatically actuated piston to force ball bearings into a collar, Figure 5. The main characteristics of this locking technique are reliability, accuracy, separation strength, and remote operation capability (through pneumatic power), and the provision for a fail-safe connection.

The fail-safe mechanism is achieved by utilizing the force generated by four springs equally placed on a circle concentric to the retaining male support stem. The multiple spring design choice was selected because of reliability and fail-safe operation. In case one of springs fails, the

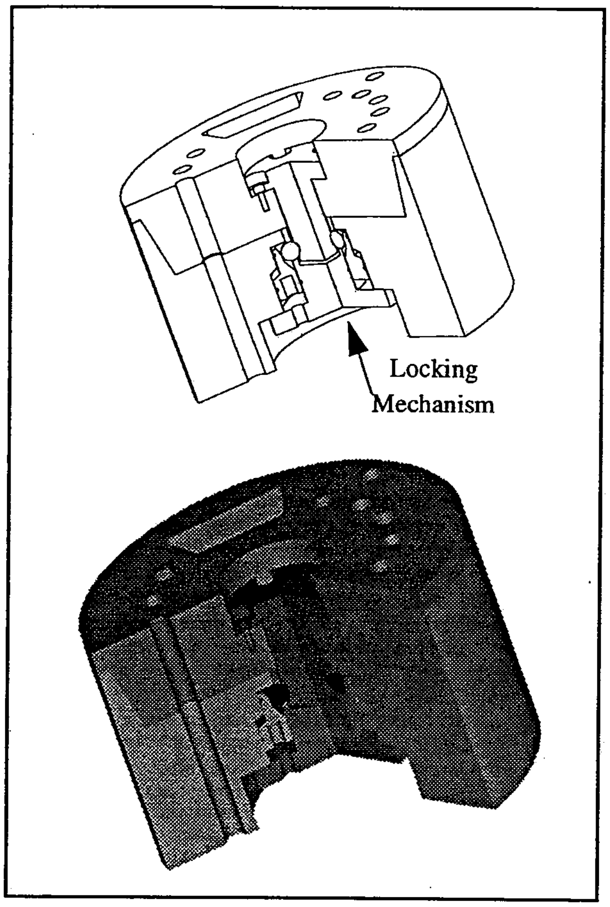

Figure 5: QCD Coupler Locking Mechanism

4.3. Electrical Connections

The electrical connections provide for both power and information transference from the base to the outbound joint actuators including the end effector. Therefore a considerable number of electrical connections of various sizes is necessary, Figure 6.

The available space on the QCD face allows for twenty-six 25-amp connections, twelve for the motors and fourteen for end effector operations. The existing end-effector tool changers provide for fifteen 5-amps, 120V lines for both power and sensor/feedback lines (PhD, 1993 Catalog). However, operations that require larger amperages, such as welding, would have to be considered separately.

The sensor and feedback lines would not need high amperages and could utilize 5-amp lines. Because of their small size, the QCD provides for up to one hundred 5-amp lines, three to seven times more than in existing end effector tool changers. The actual mating of the electrical lines is accomplished using Pogo Pins^{TR} [Augat, 1994]; a trademark for a spring activated conducting pin that rests in an electrically conductive receptacle. To provide electrical

was chosen as the proper mounting material since it is a lightweight nonconductive polymer. The pins are designed to be adhesively bonded to this type of material and assembled with a press-fit.

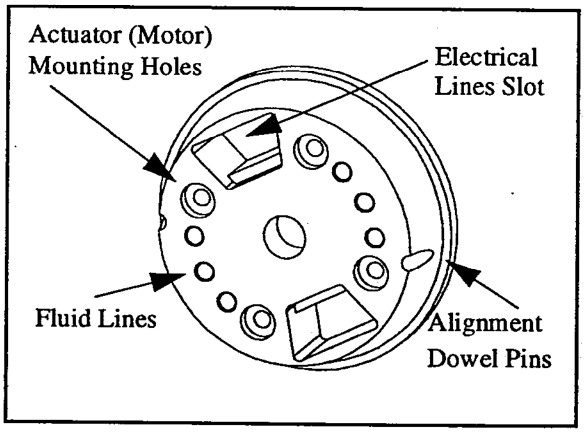

Figure 6: QCD Coupler Flat Surface Components

The QCD provides electrical power connections for four motors and sensor/feedback lines for ten devices. The modularity and expandability of the QCD design for information sharing allows for the easy replacement of the electrical sensor/feedback lines with optical fiber cables that adhere to the SERCOS (Serial Real-time Communication System) standard. In addition, if optical fiber is employed, then some of the sensor lines could easily be transformed to power lines, since a smaller number of optical fiber cables could transmit the required amount of information. The electrical connection numbering scheme has been standardized based on the geometry of the QCD.

4.4. Fluid Connection

The fluid connections accommodate moderate pressures of both hydraulic and pneumatic fluids by using O-rings for sealing, Figure 6. There are six fluid lines with one of them being a non-dedicated pneumatic line for the operation of the locking mechanism of the QCD. Existing end-effector tool changers provide four fluid interface ports (PhD, 1993 Catalog).

The position of the fluid and motor mount holes is of importance. The motor mounting configuration dictates that the retaining bolts reside on a circle. Design calculations indicate that only four bolts were sufficient even though the motor design could accommodate eight equally spaced bolts. The fluid lines, which comprise of holes nominally smaller than that of the motor mounting holes, are aligned with the motor mounting pattern. This alignment allows for a fluid line to be bored out and used as a motor mounting hole if the load requirements are ever found to be greater that what the original four mounting bolts can carry.

The design also considers the location of the fluid and electrical lines. Because each module is required to attach to any other module, all must have identical line mating configurations. We decided to place all the lines interior to the link and motor. This allowed for safe and consistent operation without the worries of contact damage to the lines while adding a more ergonomic design. Of course, this requires motor and gearing selections to have through-bore designs, which are currently available [mecos, 1994; HD Systems, 1994].

5. Comparison of Three Articulated "Modular" Robots

In this section, a comparison of three articulated type robots is given. The comparison attempts to illustrate the modular concept in an effort to recreate a PUMA 562 robot. The performance and geometrical characteristics of the PUMA 562 robot are presented by Cohen [Cohen, 1992]. In the same paper, a conceptual modular robot developed using hypothetical modules that matches in performance the PUMA 562 is also presented. [Cohen, 1992]

Table 1: Comparison of three articulated type robots

	Current Modular Robot	Cohen's Modular Robot	PUMA 562 NonModular
Reach (m)	1.2	1.2	0.92
Tip Vel. (max. payload) (m/s)		1.0	0.5
Tip Accel. (max. payload) (m/s^2)		9.81 (1 g)	9.81 (1 g)
Payload (Kg)	26.4	6.0	4.4
Static Force at the Tip (N)		210	58 (Puma 560)
Weight (Kg)	67	41	63
Deflection (mm) (No static load)	3.95*10-6	2.8	N/A
(25N static load)	5.57*10-6	3.7	N/A
(210N static load)	1.75*10-5	10.0	N/A

If we assume that all the components of our module are made out of aluminum alloy material, then a link of circular cross section will weigh approximately 5.5 Kg with an outer and inner diameter of 178 mm and 165 mm respectively (wall thickness of 13 mm). The QCD weighs approximately 7.4 kg. The motors that achieve comparable performance to that of the PUMA 562 robot are selected to have nominal output torques of 220 Nm for the base and first joint and 137 Nm for the second joint. Currently, we do not have designs for an end effector; therefore, the end comparison of the three articulated type robots (the current QCDBot modular robot, the modular robot as presented in Cohen [1992], and the non-modular PUMA 562) is presented in Table 2 for reference purposes.

6. Experimental Testing

The performance of the proposed QCD conceptual design was verified experimentally. A QCD was constrcucted and various experiments were conducted. In one experiment the operation of the quick connect disconnect mechanism was validated; and in another experiment the torsional stiffness was determined. The results of these experiments provided information which will be used for design improvements to the second generation QCD.

The first test verified the operation of the QCD. The locking mechanism was put in place and attached on the QCD body. The male and female parts were aligned, and air pressure was applied. This test was repeated numerous times, and during each time the locking and unlocking mechanism performed without any problems.

The second test was conducted in order to evaluate the torsional stiffness of the QCD male and female assembly. The test results along with other evaluated results are shown in Table 2. The angular rotation of the QCD male housing θ is evaluated using the following formula $\tan\theta = \delta/l_{gage} = (\delta_{gage} - \delta_{stand})/l_{gage}$. The term δ_{stand} represents the deflection of the lever support without the QCD attached. This was done in an effort to separate the actual deflection of the QCD from influences from the other equipment used in the test. The applied moment and angular deflection results were analyzed by fitting a linear curve. The torsional stiffness of the QCD coupler is found to be $K_{tor} = 120239.2\ N\text{-}m/rad$.

Table 2: QCD Torsional Stiffness Test Results

Weight (lb)	Moment (ft-lb)	Linear Deflection δ (*0.001 in)	Angular Deflection θ (* 0.001 rad)
50	125.0	5	1.111
75	187.5	8	1.777
100	250.0	12	2.666
125	312.5	16	3.555
150	375.0	20	4.444
175	437.5	24	5.333

7. Conclusions

There exist obvious advantages for the development of modular robots for industrial applications. These robots can be easily reconfigured and installed for pilot programs and rapidly changing manufacturing scenarios. Furthering modules to perform more tasks. This directly affects costs such as those associated with equipment capital and available floor space. In addition, a modularized system could be programmed and controlled using an open architecture controller [Cimetrix, Trellis], thus reducing or eliminating problems of compatibility between the modular robot mechanical and electrical hardware, controller software and hardware, and manufacturing processes. Therefore, implementing such a modular system would drastically improve setup time, production throughput while reducing manufacturing costs, capital expenditures and downtime.

In this paper, we introduced the QCD coupler, the mechanical hardware backbone in the development and implementation of a rapidly reconfigured modular robotic system. The various components of the QCD, and their role and functionality were discussed. The QCD allows each module to quickly and automatically connect to any other module providing internal interface ports for all fluid, electrical power and information lines. The proposed QCD was manufactured and tests were conducted to evaluate its performance with satisfactory results. The structural performance of the QCD was verified through the experimental results which were compared with results in the literature. This comparison proved that the QCD coupler concept should be considered for use in the development of reconfigurable robotic manipulators.

The conducted tests proved the basic concept and provided information to support important design improvements. Currently, we are in the process of integrating the QCD with an actuator and link to form a modular unit. We are confident that by the time of the conference, we will be able to present pictures of a complete module (QCD, link, actuator), as well as pictures of a two link modular manipulator system.

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