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Design and Implementation of a Lightweight, Large Workspace, Non-Anthropomorphic Dexterous Hand

The design and implementation of a novel dexterous robotic hand is described. To provide flexibility of application the design features three fingers, each position or force controllable in X-Y-Z, and a large workspace (400 mm dia. × 75 mm deep). These requirements plus the need for adequate strength (i.e. force and stiffness) are in conflict with the need to keep the mass within the payload capacity of common robots. These contrary objectives are met by designing a novel hybrid parallel-serial finger mechanism, a lightweight frame and pneumatic servos for finger actuation. The implemented design is verified experimentally, and may be scaled for other applications.

1 Introduction

For many years it has been recognized that a robotic hand with the workspace and dexterity to handle a wide range of objects would be an important development. Today, the trend towards manufacturing near one-of-a-kind products to meet customer demands is also driving the need for greater manufacturing flexibility.

While substantial progress has been made in the development of dextrous anthropomorphic robotic hands, these devices are not well suited to automated manufacturing. Wright and Bourne [1] observed that the manufacturing world is more demanding and narrower in scope than the everyday world from which our hands evolved. In 1997, Bekey [2] concluded that the robot hands which have been built are complex, expensive and unreliable. Few researchers have investigated non-anthropomorphic dexterous hands. For reviews of the relevant literature please see [1, 3].

In this paper the design and implementation of a novel lightweight, large workspace, non-anthropomorphic dexterous hand is described. The design process, completed design, and initial experimental results are summarized.

2 Design Specifications

2.1 Finger Design, Number and Degrees of Freedom. As in many previous hand designs, the decision was made to use three fingers with the current design. This limits complexity and will produce secure, precise grasps of generic 3D objects if the fingertip design provides either sufficient friction forces or a form closure type of constraint. The hand will also be designed to allow alternate fingertips to be interchanged easily.

It is readily apparent that increasing the number of DOF of each finger will increase the dexterity and flexibility of the hand at the cost of increasing its complexity. Since a high degree of flexibility is the overall goal, each finger will have three computer controlled DOF (X, Y and Z). By actuating all three fingers in X-Y-Z, the hand will also allow the compliance of the held part to be actively controlled in 3D space (i.e. X, Y, Z, θ_X, θ_Y and θ_Z). As observed by many researchers ([1, 6] for example), control of compliance is important for the successful automation of many manufacturing tasks, and of the insertion process in assembly in particular.

2.2 Scalability and Workspace. Although the hand will be designed to have a large workspace, realistically this workspace needs only to cover the range of part shapes and sizes encountered in the intended manufacturing task, i.e. the same hand would not be intended for use in electronics assembly and in aircraft assembly. At the same time it is intended that the design be scalable in terms of power and size to allow it to be used in many tasks.

The particularly challenging task for which the hand prototype will be built is automotive body-in-white assembly (BIWA). Since BIWA involves a large range of complex shaped parts (about 300–400 per car) and numerous dedicated tools, it is a good test case for the flexible hand design. Here the parts are typically less than 400 mm long and 75 mm deep, so a cylindrical workspace 400 mm dia. × 75 mm deep is ideal.

2.3 Force, Stiffness and Mass. The hand must produce sufficient internal grasping forces to secure the object without damaging it. For the BIWA application a force range of 10–150 N is expected to be adequate. In addition to resisting the grasping forces the hand's mechanical structure must withstand gravity, inertial and assembly forces. Taking the required accuracy of ± 0.5 mm into account, and assuming the maximum externally applied force is ≤ 50 N, the required minimum stiffness is 100 N/mm.

A lower hand mass would allow a smaller, less expensive robot to be used. A tradeoff exists with this desirable characteristic and the stiffness, workspace and DOF requirements. Since the latter are greater contributors to the application flexibility of the hand, they will be given priority in the design process. The target for the hand's mass is 20 kg, which is within the typical payload capacity for a mid-size industrial robot. The design specifications for the hand are summarized in Table 1.

3 Mechanism Synthesis

3.1 Type Synthesis. Several mechanism types capable of providing the three DOF Cartesian motion required for each of the fingers were considered. The traditional serial designs used for robot manipulators were rejected since they tend to provide inferior stiffness and accuracy in comparison to parallel mechanism designs of the same mass. The chosen design consists of a "bipod" parallel mechanism (of type R-P-R-P-R, where R = revolute joint and P = prismatic actuator) to provide the X-Y motion coupled serially to a single prismatic actuator for the Z axis motion. Its kinematic diagram is shown in Fig. 1. This choice can be justified by considering the size of the required X-Y motions (roughly 200 mm × 350 mm assuming the finger workspaces are

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Table 1 Summary of design specifications

Grasp type:	Fingertip
Number of fingers:	Three
DOF per finger:	Three
Finger control:	Position and force
Workspace:	400 mm dia. × 75 mm deep
Positional accuracy:	±0.5 mm
Grasping force:	10–150 N
Stiffness:	>100 N/mm
Mass:	20 kg
Other:	Scalable design

to be equal in size) in comparison to the size of the required Z motion (75 mm). A parallel design is superior for the relatively large X-Y motions while the stiffness and accuracy benefits of a parallel design over a serial one for the small Z motion are minimal and do not warrant the additional difficulties involved.

3.2 Dimensional Synthesis. Here the dimensional synthesis problem involves the solution of the mechanism parameters for each finger, plus the angle and radius of each of the mechanisms' origins relative to the origin for the total workspace. As noted in Section 2.2, a total workspace of 400 mm dia. is desired. To reduce complexity, identical mechanisms will be used for all fingers. A further decision was made not to consider overlapping the finger workspaces as this reduces the size of the total workspace and does not offer any great improvements in grasping flexibility. Under these conditions the total workspace size is optimized if the finger mechanisms are placed at 120° intervals around a circle whose radius equals the maximum Y extension of each mechanism. This configuration is shown in Fig. 2.

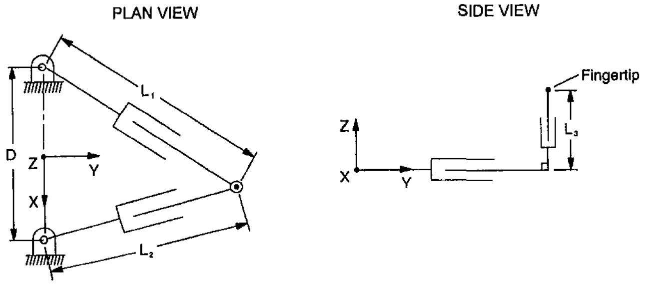

Fig. 1 Kinematic diagram for the hybrid parallel-serial finger mechanism

What remains is the solution of the finger mechanism parameters which give the largest non-overlapping finger workspace. The same actuators will be used for L_1 and L_2, so the kinematic parameters are: $L_{\min} = \min(L)$, $L_{\max} = L_{\min}$ + actuator stroke, and D, the baseline distance. The mechanical advantage of the mechanism will also be considered. The mechanism has a singularity whenever the three revolute joints are collinear, and cannot resist forces perpendicular to the line of collinearity. To maximize the useful workspace the parameters will be chosen to avoid this singularity. At the same time the actuator stroke should be minimized since it adds mass to the hand. A numerical study was performed to determine the near-optimum parameters [4]. Sample results are shown in Fig. 3 for the stroke = 150 mm. In 3(*a*), with an $L_{\min}$ of 52 mm the useful workspace is smaller than shown since a large portion of it lies close to the singularity line $y = 0$. As shown in 3(*b*), increasing $L_{\min}$ to 104 mm avoids the singularity, while decreasing D from 197 to 99 mm appears to greatly increase the size of the workspace. However, mechanical interference would make the bottom portion of the workspace unreachable in practice. Keeping $L_{\min}$ constant and increasing D to 295 mm yields a workspace similar to 3(*a*), as shown in 3(*c*). The workspace for the final parameters, $D = 197$ mm, $L_{\min} = 104$ mm, $L_{\max} = 254$ mm, is shown in Fig. 3(*d*). The hand's workspace equals the union of three X-Y finger workspaces spaced at 120° intervals and extruded by 75 mm in the Z direction. The final workspace has dimensions of ~400 mm dia. × 75 mm deep.

4 Mechanical Design

The mechanical design of the finger mechanisms and hand frame focused on the need for both high stiffness and low mass. Due to space limitations, only the novel features of the designs will be highlighted. Complete design information is provided in [4].

4.1 Finger Mechanism. The bipod parallel mechanism design provides high stiffness in the X-Y plane since its truss structure will place its members into compression and/or tension under load rather than bending. However, forces applied at the finger tip

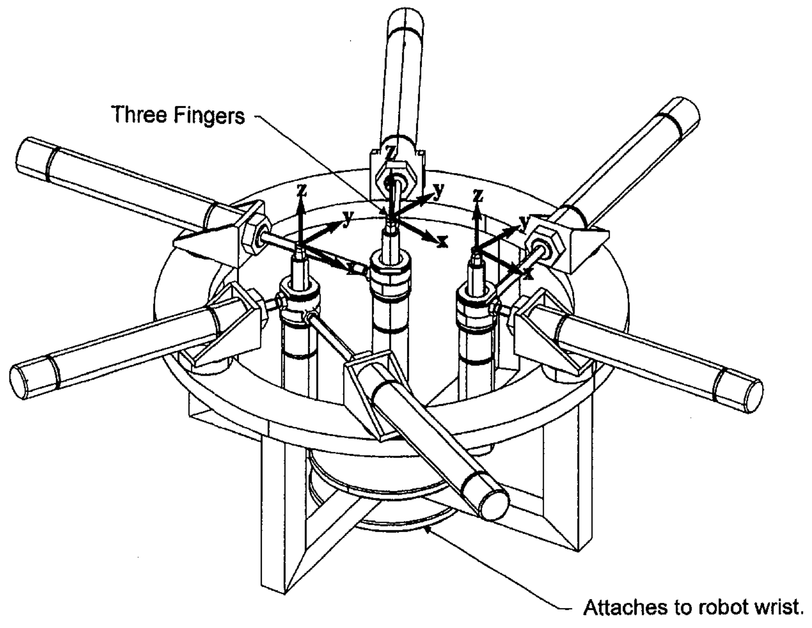

Fig. 2 Overall configuration for the gripper

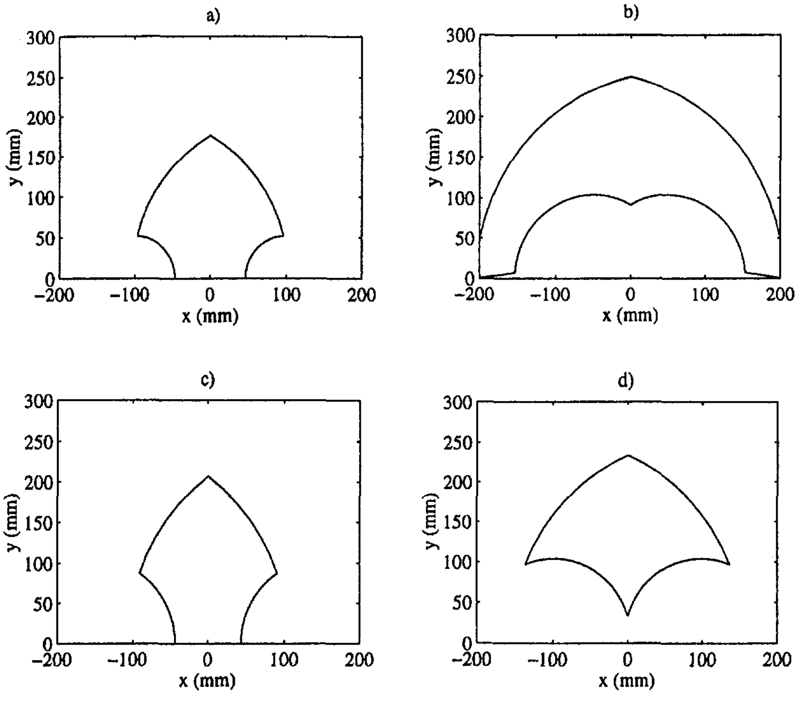

Fig. 3 Effect of L_{min} and D on the X-Y workspace of a finger mechanism with 150 mm stroke actuators: (*a*) L_{min} = 52 mm, D = 197 mm, (*b*) L_{min} = 104 mm, D = 99 mm, (*c*) L_{min} = 104 mm, D = 295 mm, and (*d*) L_{min} = 104 mm, D = 197 mm

will create a bending moment which will bend the truss out of plane. To solve this problem a double truss structure was designed. With this structure, fingertip forces are resolved into reaction forces which are transmitted through each truss to the hand's frame.

To provide greater stiffness than possible with the actuators

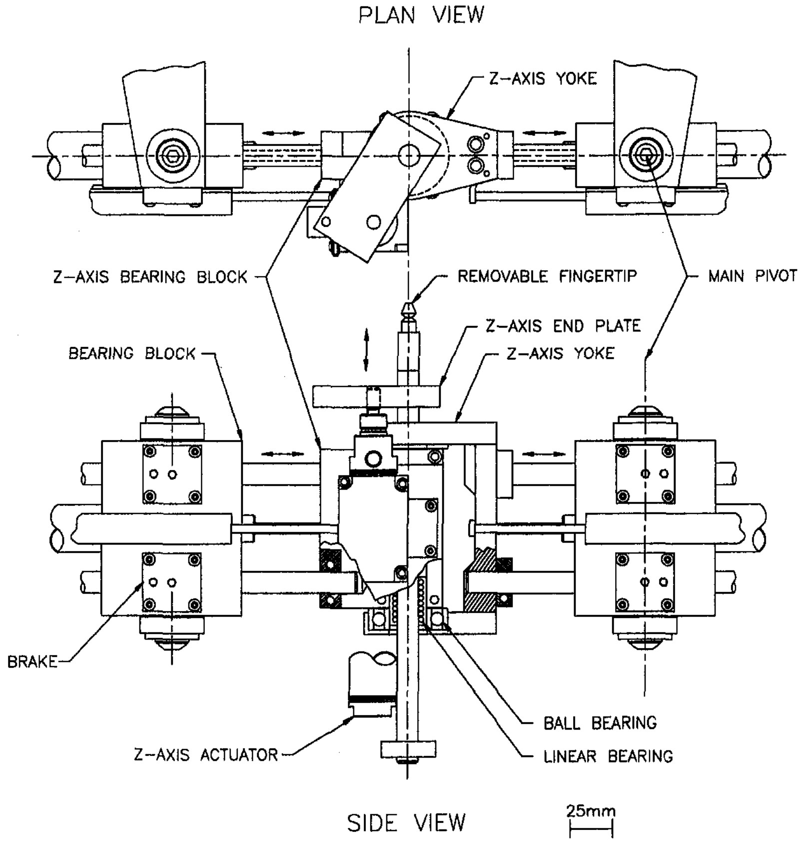

Fig. 4 Mechanical design of the finger mechanism

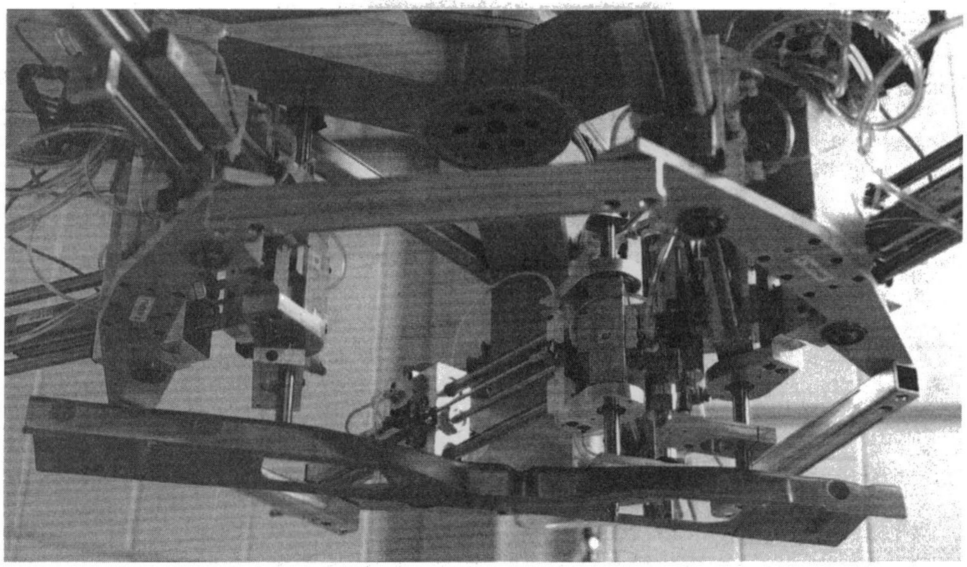

Fig. 5 Photograph of the implemented design holding a sheet metal part (patent pending [5])

alone, brake mechanisms were added to allow the actuators to be locked. For compactness the brakes were incorporated into the bearing blocks for the prismatic actuators, as illustrated in Fig. 4. Four devices are used with each actuator. Each device consists of a 32 mm dia. pneumatic piston which clamps against one of the guide rods. Based on friction coefficient tests with a prototype, the total braking force per actuator is ~350 N.

For low mass and compactness, the design combines the middle revolute joint with the Z-axis prismatic actuator. As shown in Fig. 4, the linear bearings and guide rod for the Z-axis are encircled by the ball bearings for the revolute joint. The Z-axis bearing block is rigidly mounted to one of the X-Y plane actuators, and a yoke is mounted to the second actuator. This yoke straddles the bearing block and preloads the revolute bearings to provide a stiff, slop free joint. The Z-axis guide rod forms the base of the hand finger. The fingertip is removable, allowing alternate designs to be interchanged as needed.

4.2 Frame Design. The frame will support the three finger mechanisms and attach to the robot's wrist. With the requirements for high stiffness and low mass in mind, a welded space frame structure employing hollow aluminum extrusions was designed. The cross-sectional dimensions of the frame members necessary to meet the stiffness specification were determined from a theoretical analysis of the frame's stiffness. Theoretical and experimental stiffness values are compared in Section 5. The completed frame is shown in Fig. 5.

5 Testing

5.1 Dynamic and Steady State Positioning. Chosen primarily for their high power to weight ratio, the implemented design is actuated by pneumatic servos. The dynamic finger positioning performance was tested for step inputs ranging from 0.1 mm to 60 mm. Risetimes of ≤0.15 s, overshoots of ≤3 percent, and settling times ≤ 0.8 s were achieved.

The steady state accuracy of the finger positioning was tested using a coordinate measuring machine. The accuracy ranged from a minimum of ±0.1 mm when the actuators were near fully retracted, to a maximum of ±0.4 mm when the actuators were near fully extended, so the accuracy specification of ±0.5 mm was met. This accuracy pattern was expected since errors such as squareness have a greater effect on the fingertip's position when it is outstretched.

5.2 Mass and Stiffness. The mass of the completed gripper was found to be 25 kg. While this exceeds the target by 5 kg, it is still within the payload of many industrial robots. For purposes of comparison, a previously built hand, employing DC motor driven ball screws, had a two-axis servoable workspace of 100 × 100 mm and a mass of 9 kg. Scaling the previous design to meet the new design's capabilities would give it a mass of ~162 kg, or 650 percent of the new design's mass.

The stiffness of one of the fingers was measured at nine positions covering its workspace. At each position the brakes were activated to lock the actuators. The measured stiffnesses are compared to those predicted by the theoretical analysis in Table 2. With the exception of position **I**, the average modelling error is 13 percent. In position **I** all actuators were fully retracted and the theory underpredicted the actual stiffness by 365 percent. In all cases the stiffness met the specification for being >100 N/mm.

5.3 Grasping. A few preliminary grasping experiments were performed to test the gripper's ability to pick up and hold a range of objects. Three distinctly shaped sheet metal automotive parts were chosen as representative of those involved in the BIWA application for these tests. Their approximate dimensions are: 300 × 225 × 50 mm, 425 × 100 × 75 mm and 625 × 125 × 35 mm (length × width × height). Each grasp was executed by moving two of the fingers under position control to taught grasping locations while the third finger completed the grasp under force control. The gripper is shown holding one of the test parts in Fig. 5.

Table 2 Comparison of theoretical and measured finger stiffnesses

	Theoretical stiffness		Measured stiffness	
X-Y-Z position (mm)	K_x (N/mm)	K_y (N/mm)	K_x (N/mm)	K_y (N/mm)
A (0, 234, 75)	120	160	140	180
B (0, 234, 38)	220	320	260	350
C (0, 234, 0)	390	580	470	770
D (0, 150, 75)	170	160	180	180
E (0, 150, 38)	270	320	340	420
F (0, 150, 0)	500	580	490	880
G (0, 33, 75)	170	160	180	180
H (0, 33, 38)	320	320	310	370
I (0, 33, 0)	270	250	560	650

6 Conclusions

A lightweight, large workspace, non-anthropomorphic dexterous hand was designed and implemented. To provide flexibility of application in manufacturing tasks, the design includes three fingers, each capable of being either position or force controlled in X-Y-Z. The conflicting workspace, strength, and mass requirements were met by designing a novel hybrid parallel-serial finger mechanism, a lightweight frame and pneumatic servos for finger actuation. The implemented design has a workspace of ~400 mm dia. × 75 mm deep, and a mass of 25 kg. A limitation of the design is that its overall size is roughly three times larger than its workspace so it is not well suited for grasping objects which are difficult to access.

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