Automation and Robotics in Construction XVI © 1999 by UC3M

DEVELOPMENT OF HYBRID DRIVE PARALLEL ARM FOR HEAVY MATERIAL HANDLING

Tatsuo ARAI*1, Kei YUASA*1, Yasushi MAE*1, Kenji INOUE*1, Kunio MIYAWAKI*2, Noriho KOYACHI*3, Hirokazu ABE*4, Isamu ISHII*5, and Kazuya KIGAWADA*6

*1 *Osaka University, arai@sys.es.osaka-u.ac.jp,*
*2 *Hitachi Zosen Co.,* *3 *Mechanical Engineering Labotatory,*
*4 *Shimizu Construction Co.* *5 *Kajima Co.,* *6 *Hazama Co.*

Abstract: This paper presents a hybrid cylinder/wire drive parallel arm. Its workspace is analyzed for the application of manipulating heavy materials in construction and ship building industries. The conventional Stewart platform and a multiple wire drive mechanism are compared, and hybrid drive mechanisms are considered in analysis and designing. The total number of cylinder and wire is fixed to seven based on the force closure principle. The actuated cylinder force and wire tension are analyzed based on the kinematics and statics formulated for an arbitrary combination of cylinder and wire mechanism, then its work space is evaluated. An arm mechanism with three cylinders and four wires is proposed in the application of manipulating a precasting concrete board with $3 \times 6 \times 0.2$[m] in size and 10[t] in weight.

Keywords: heavy material handling, manipulation, parallel mechanism, kinematics, statics

1 INTRODUCTION

The industrial robot has been applied to welding, spraying and assembling tasks in manufacturing factories. The high performance capabilities of manipulator, such as its excellent repeatability, positioning accuracy and high speed, contribute to increasing factory productivity. Crane is a major handling tool for heavy materials in construction and shipbuilding fields, since it is capable of holding and translating them vertically and horizontally with a length of wire in a simple way. However, swing motion and rotation are generated and it is rather difficult to control them and to obtain accurate object positioning and orienting. Therefore, workers should support materials by their hands to suppress the vibration and to position them accurately. These tasks are dangerous for human workers and then their productivity are rather limited.

Although human workers can be replaced by intelligent robots and coordinated motion of crane and robot is proposed[1], this may lead to a complicated and large system and thus a sophisticated control might be inevitable. The coordination of multiple cranes is another method, but it is entirely difficult to control each crane for positioning and orienting a heavy material. A new robot technology is required including handling arm hardware and control software to promote automation in the industries.

In the IMS IF7 Project researches on innovative production system have been developed to increase productivity and to promote automation in construction and ship-building industries where huge heavy materials and structures are processed and assembled on cite[9]. The robotic arm will play an important roll in the automation. This paper proposes a hybrid drive parallel arm by wires and cylinders in order to design a compact handling arm enlarging its workspace. It is aiming at developing dexterous arm capable of controlling 6 d.o.f. motion of a heavy material. The paper discusses a basic concept of parallel mechanism with hybrid actuation, comparisons and evaluations of some types of hybrid mechanisms based on its kinematics and statics, and finally introduces a designed prototype arm.

2 IDEA ON HYBRID DRIVE PARALLEL ARM

A dexterous arm capable of handling and assembling a huge heavy material is required to promote the automation in the project. A parallel mechanism, where an end-effector is actuated by multiple groups of linkages in parallel, is one of candidates for heavy material manipulation, since it has an advantage of large force generating ability over the conventional articulated arm mechanism. The Stewart platform is a well-known parallel mechanism and has good reputations in the application to flight simulators, however, the only problem is its limited workspace. Interference in linkages and small cylinder strokes limit its workspace in comparison with conventional serial arms. A multiple wire drive mechanism is classified as a type of parallel mechanism and it can be applied to design a compact handling arm, since a wire actuator has a light mass in movable mechanism and is capable of generating larger force than a cylinder actuator[2–5, 8]. The wire drive mechanism has redundancy in actuation, since a wire generates only tension and it should have one more degree of freedom than the actual d.o.f. required at its end according to the principle of force closure[4, 6]. Moreover, wires should be arranged so as to surround a manipulated object and this may again limit its workspace.

We will propose a hybrid drive parallel arm by wires and cylinders in order to design a compact handling arm enlarging its workspace. It is aiming at developing dexterous arm capable of controlling a full 6 d.o.f. motion of a heavy material. The main idea is to enlarge the limited workspace of the wire drive mechanism by replacing some wires with cylinder. Since the cylinder is capable of generating tension and compression, the actuators can be arranged in one side to a manipulated object, i.e. they do not have to surround the object as in the wire drive mechanism, and this enables the mechanism to enlarge its workspace. A wire drive mechanism can be analyzed based on the force closure principle, and it suggests that the mechanism should have one more actuator than its actual motion d.o.f. Thus, the hybrid drive arm requires total seven wire and cylinder actuators, if 6 d.o.f. required, and several types of mechanisms with this constraint may be considered in the following.

3 COMPARING MECHANISMS

Various hybrid arms with different combination of cylinders and wires are compared with the conventional Stewart platform and wire drive mechanism, evaluating their workspace with orientation based on the kinematics and statics[7], which are not discussed in this paper because of its limited space. It is difficult to compare all the combinations of actuator, link and scale, then following conditions are assumed.

3.1 Conditions of analysis

1) Scale of mechanism : R1,R2 are the position of the link attachment points on the base plates. r1,r2 are the position of the link attachment points on the end plates as shown in **Fig.1**. In this paper, they are defined R_1=2.0[m], R_2=1.5[m], r_1=0.5[m], r_2=0.3[m].
Stroke of links:

$$l_{wi} \geq 0 \ : \ wire \qquad (1)$$

$$l_{cmin} \leq l_{ci} \leq l_{cmax} \ : \ cylinder$$

where l_{cmin}=5[m], l_{cmax}=9[m], stroke=4[m].
Interference in linkage : A workspace of parallel mechanism is limited by interference between each links. The minimum distance d determined by following conditions

$$d > d_c \ : \ cylinders$$

$$d > d_w \ : \ wires \qquad (2)$$

$$d > (d_c + d_w)/2 \ : \ cylinder, wire$$

d_c, d_w denote diameter of each cylinder and wire, respectively, and d_c=200[mm], d_w=16[mm].

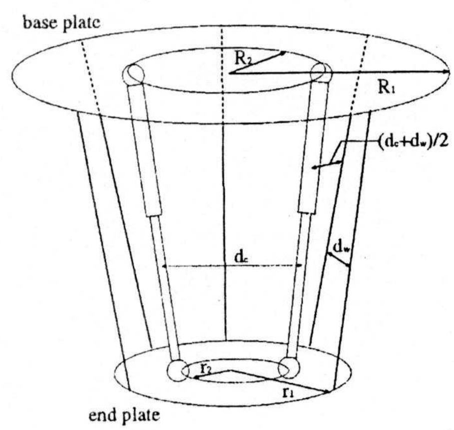


Fig.1. Dimension of hybrid arm

2) Condition for force actuated at link : A wire actuator generates only tension, while cylinder generates either tension and compression. According to the statics, forces at each link can be controlled by adjusting inner force. Inequalities for each link are as follows:

$$-M \leq \tau_i \leq M \ : \ cylinder \qquad (3)$$

$$0 \leq \tau_i \leq N \ : \ wire$$

where τ_i is the i-th actuator output and is derived from the statics, M(maximum tension and compression)=2000[kgf], and

N(maximum tension of wire)=7000[kgf]. If τ_i satisfies these seven simultaneous inequalities, the forces produced at links are obtained.

3) Object manipulated : A weight W is at an offset d from the end plate(**Fig.2**). The purpose is to handle heavy material(ton order), and we define W=10[tf], d=1.8[m] for the analysis.

3.2 Criterion of evaluation

The workspace is determined under the constraints on the interference between the links and the limitation of cylinder force and wire tension(**Fig.2**).

1) A radius h on the plane perpendicular to z axis in the base coordinate system is fixed. And we take points on the center and the circumference of a circle at every $\Delta\alpha$ degree. In this paper, h=0.5[m], $\Delta\alpha$=1[°].
2) The object coordinate system $x_w y_w z_w$ is attached to the center of gravity of the object. In each point, the orientation θ_x, θ_y is examined around x, y axes with fixing the origin of the object coordinate system. The rotational angle around z axis is fixed in the analysis. Inverse kinematics and statics are calculated at every $\Delta\beta$ degree around x, y axes. The solutions are examined whether they satisfy the above conditions. Then, range of rotational angle θ_x, θ_y are obtained at every point. In the analysis $\Delta\beta$=1[°].
3) The range of rotational angle is examined by the method of (2) at every Δz, where Δz=0.1[m].

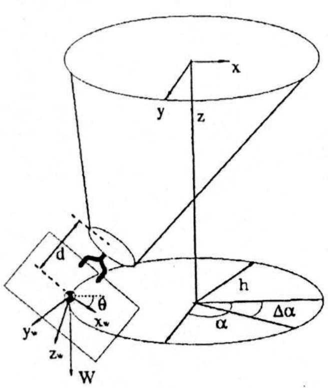


Fig.2. Object and how to obtain range of rotational angle

3.3 Mechanism and workspace

Symmetrical configurations are considered in the comparisons and evaluations. The total number of cylinder and wire is fixed to seven based on the force closure principle. But this paper does not address a mechanism with more four cylinders because they become very large in size.

3.3.1 Stewart platform (C6)

Conventional Stewart platform is compared. The mechanism is illustrated in **Fig.3**.

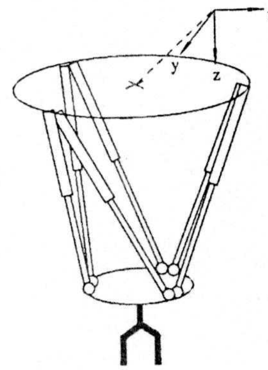


Fig.3. Configuration of Stewart Platform (C6)

The range of rotational angle of the SP is only 1 degree and the range of translation in z is 3.0[m]. The range of motion in the SP is rather small because the force of cylinder is limited.

3.3.2 Wire drive SP(W6)

In this mechanism, cylinders are replaced with wires(see **Fig.4**(a)). According to force closure principle, this mechanism is lack of wire, but we think it is supplemented by gravity. The range of rotational angle is shown in **Fig.4**(b). It is larger than that of the C6 type because of its larger force actuation in the wire, however, this type is not applicable, since this is not a full 6 d.o.f. mechanism. In the figure, the horizontal axis represents position α, and the vertical axis represents orientation θ_x, θ_y. In the following figures, z is fixed at 6.0[m] (z = 9.0[m] for the C3W4 with rod), because the difference in the rotational angle around z axis is small as in the other mechanisms.

3.3.3 C1W6 type

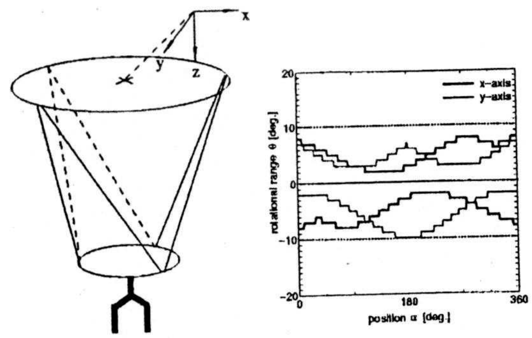
This mechanism has one more cylinder than the W6 type between the base plate and the end plate as shown in **Fig.5**(a). The range of rotational angle is shown in **Fig.5**(b).

3.3.4 C2W5 type

This mechanism consists of two cylinders and five wires. Each link is placed in a symmetry pattern (see **Fig.6**). It has singular points in the center of its workspace, therefore it is no longer rigid and there are certain directions in Cartesian space along which the device cannot support any force or moment. Any other mechanism of this type has also singular points and is not feasible for arm.

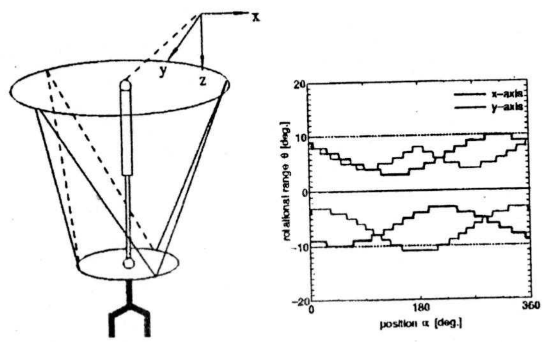
3.3.5 C3W4 type

This mechanism consists of three cylinders and four wires. Two different types are illustrated in **Fig.7** and **Fig.8**(a). In type 1, four wires are placed at every 90 degree at the end plate. In type 2, four wires are placed with two pairs at the end plate. Type 1 has singular points, the same as in the C2W5 type. The range of rotational angle of



(a) Configuration (b) rotational angle

Fig.4. Configuration and range of rotational angle of W6



(a)Configuration (b)rotational angle

Fig.5. Configuration and range of rotational angle of C1W6

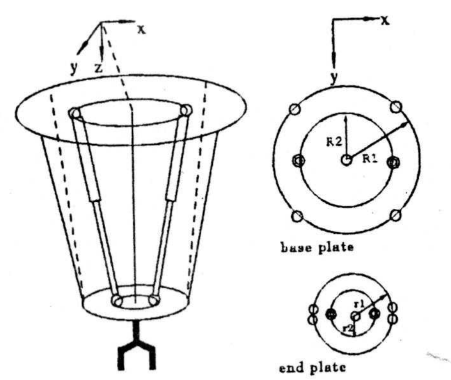


Fig.6. Configuration of C2W5

type 2 is shown in **Fig.8**(b).

3.3.6 C3W4 with rod type

In order to enlarge range of rotational angle, large moment at the end plate is required. Thus, adding one rod between the cylinders and the end plate is proposed as shown in **Fig.9**(a). The range of rotational angle is shown in **Fig.9**(b), where the length of rod is fixed to 3.0[m]. The range of rotational angle is much larger, however, the scale of arm becomes much larger than the others.

3.4 Comparison of mechanisms

1) C6 The range of rotational angle is very small because of the limitation in the force of cylinder.
2) W6 This mechanism has no full 6 d.o.f. and is not applicable for arm.
3) C1W6 The range of rotational angle is enlarged by adding one cylinder to W6.
4) C2W5 The mechanism has singular points at the center of its workspace and is not applicable.
5) C3W4 The range of rotational angle is very small because the moment at the end plate is limited.
6) C3W4 with rod The range of rotational angle is large enough, but the size becomes large because of its added rod.

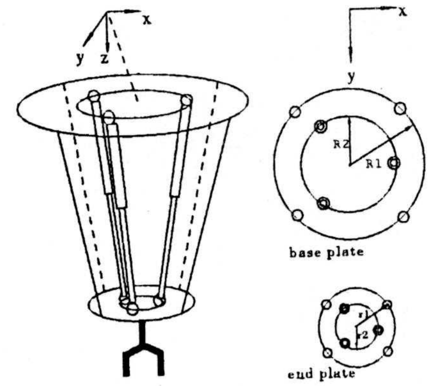
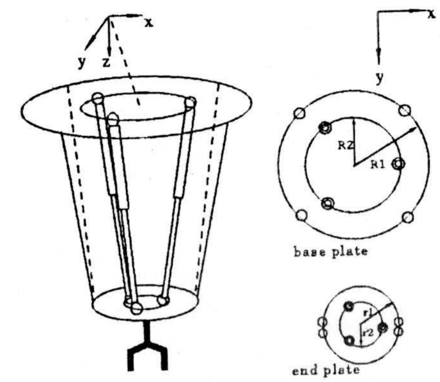
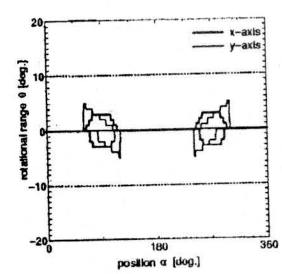


Fig.7. Configuration of C3W4 type1

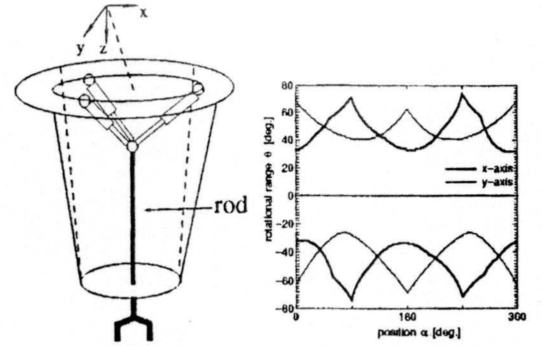


(a) Configuration of C3W4 type2



(b) rotational angle

Fig.8. Configuration and range of rotational angle of C3W4 type2



(a) Configuration (b) rotational angle

Fig.9. Configuration and range of rotational angle of C3W4 with rod

4 APPLICATION IN CONSTRUCTING MIDDLE SCALE APARTMENT BUILDING

4.1 Specification of the application

Automation in the construction of middle scale apartment building is considered in our concept as in **Fig.10**. The main structures, floors and walls, are composed of a precasting concrete(PC) board with a size of $3 \times 6 \times 0.2$[m] and a weight of 10[tf]. The workspace of arm is specified by the required motion in handling and assembling a PC board. It should be carried over 3[m] height of one floor, then the workspace is specified to be a cylindrical volume with $\phi 1 \times 3.5$[m]. Orienting motion is required in the assembling process, and its range should be over $\pm$ 10[deg].

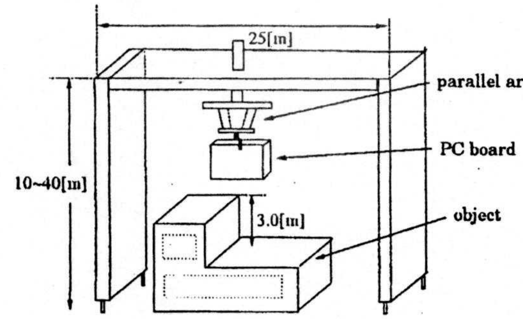


Fig.10. system of construction

4.2 Arm configuration required in the application

The previous discussion suggests the C3W4 with rod type meets the application, however, the cylinder stroke limits its longitudinal motion range. The increase of the stroke results in the increase of the arm itself. One solution may vary the length of the rod passively to increase the motion range as well as to limit the cylinder stroke as shown in **Fig.11**. Since the rod should be rigid when the arm works, the lock mechanism is attached to fix the rod length as required, typically at two points, at its top and bottom. When it goes downwards the rod moves freely pulled by gravity and controlled by the four wires. When it locates an object at the bottom end the rod is fixed and the object is controlled by all the cylinders and the wires coordinately.

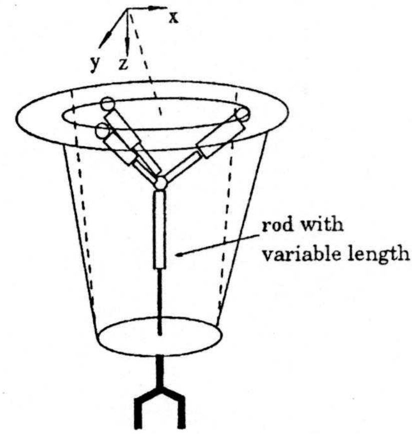
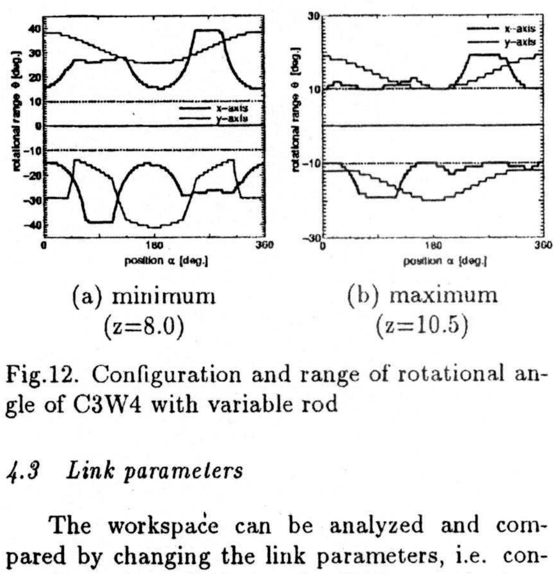


Fig.11. Configuration of C3W4 rod with variable length



(a) minimum (z=8.0) (b) maximum (z=10.5)

Fig.12. Configuration and range of rotational angle of C3W4 with variable rod

4.3 Link parameters

The workspace can be analyzed and compared by changing the link parameters, i.e. connecting points of wires and cylinders at the base plate, radius of the end plate, rod length, then the optimum values are selected to maximize the workspace volume. Table 1 shows the selected parameters and **Fig.12**(a), (b) show the results of the range of rotational angle at the top and the bottom length of the variable rod. **Fig.13** shows mechanism of the prototype, and **Fig.14** shows the figure of the prototype.

5 CONCLUSIONS

The paper has mainly proposed a new hy-

Table 1. Value of design parameters

	Length [m]		Length [m]
R_1	2.1	r_1	0.5
R_2	1.05	L	3.5-6.0

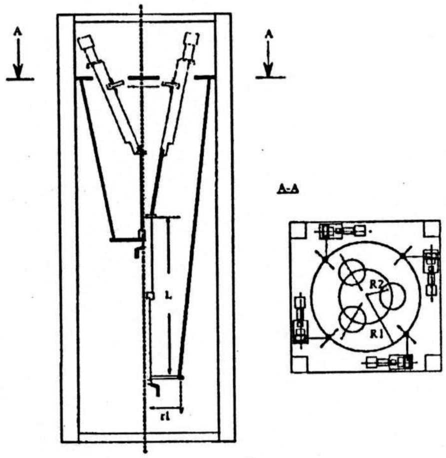


Fig.13. Mechanism of the prototype

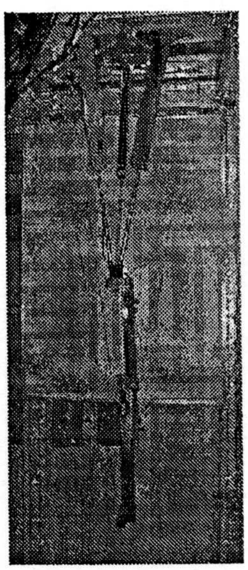


Fig.14. Figure of the prototype

brid drive parallel arm aiming at the application of handling and assembling a heavy material in the construction and the shipbuilding industries. The paper discussed the kinematics and the statics analyses of the hybrid arm, then compared and evaluated several types of mechanisms having symmetrical configuration and link arrangement. Finally, the prototype arm was introduced by specifying its link parameters in the application of constructing a middle scale apartment building as a test bed. The prototype has been built and its motion controller and intelligent system including teleoperation and sensor feedback control are now under development. This research work has been done in the IMS International Project. The authors would appreciate the IMS Promotion Center and the members of the IF7 projects for their kind supports.

REFERENCES

[1] H.Osumi and T.Arai : "Cooperative Control between Two Position-controlled Manipulators", Proc. IEEE Int. Conf. on Robotics and Automation, Vol.3, pp.1509-1514, 1994.

[2] H.Osumi, T.Arai : "Heavy Object Handling System by Cooperation of a Robot and a Crane with Multiple Wires", Proc. The 13th Int. Symp. on Automation and Robots in Construction, pp.113-120, 1996.

[3] K.Homma and T.Arai,: "Design of an Upper Limb Motion Assist System with Parallel Mechanism",Proc, IEEE Int. Conf. on Robotics and Automation, pp.1302-1307,1995.

[4] S.Kawamura,W.Choe,S.Tanaka,and S.R.Pandian : "Development of an Ultrahigh Speed Robot FALCON using Wire Drive System", Proc. IEEE Int. Conf. on Robotics and Automation, Vol.1,pp215-220,1995.

[5] Landsberger,S.E.,and Sheridan, T.B. : "A new design for parallel link manipulators", Proceedings of the 1985 IEEE International Conference of Systems,Man and Cybernetics,pp.812-814.

[6] Y.Shen, H.Osumi and T.Arai :"Set of Manipulating Forces in Wire-Driven Systems", Proc. IEEE/RSJ Int. Conf. on Intell. Robots and Systems, Vol.3,pp.1626-1631,1994.

[7] Robert S. Stoughton and T.Arai: "A Modified Stewart Platform Manipulator with Improved Dexterity",IEEE Transactions on Robotics and Automation,Vol.9,No.2,pp166-172,1993.

[8] S.Tadokoro, S.Nishiok, aet al.:"On Fundamental Design Of Wire-Driven Parallel Manipulators With Redundancy", Proc.Japan/USA Symposium on Flexible Automation, 1, pp.151-158 , 1996.

[9] Technical Report on "Studiy on Innovative and Intelligent Field Factory Domestic Feasibility Study for IMS", IMS Promotion Center, 1998