A Target-Oriented Design of a Robot Arm Assisting PWD at Working Place

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Abstract

This paper presents a systematic set of procedures in accordance with Target-Oriented Design(TOD) methodology for the development of a robot arm assisting PWD at working place. As the outcome of TOD, a robot arm has been designed and prototyped to carry out two tasks, 'circuit test of PCB' and 'soldering inspection and repairing of PCB with solder'. The robot has been used and evaluated by handicapped workers at an assembly line for electronic devices of a company in Korea.

1. Introduction

This paper focuses on the development of a robot arm assisting the *People With Disabilities*(PWD) at working place. According to *Target-Oriented Design* (TOD) procedure, a robot arm has been systematically designed and prototyped. The resulting robot arm was tested and evaluated at 'Mugunghwa Electronics,' a company where many PWD are at work. Provided below are the background and context for our endeavor.

It is well known that most of rehabilitation robotic systems have been intended to help cure and assist PWD for daily life[1-5]. For examples, MANUS is intended to assist for numerous daily living tasks at home, at work, and outdoors[3]; KARES II helps PWD with 12 tasks important for daily life[5].

While the effort above is still very important, it is valuable to pose the following question: *Suppose these robots worked perfectly, would PWD feel happy?* The answer – they may still think themselves as burden to the society unless they can do something useful and productive – leads to the rationale and necessity of the type of robots dealt in this paper. In fact, we have observed that PWD able to do productive works are *very* happy with their ability to contribute to the society.

There are several research activities on robot systems assisting PWD to do work[6-8]. RAID helps PWD on wheelchair to do work such as opening and handling books and dealing with Papers[6]. IRVIS helps PWD to do inspection work by using a digital video camera[7]. And, ProVAR carries out several tasks in office environment, with voice recognition system and head motion tracking system[8].

The systems mentioned above mainly assist PWD working in offices or laboratories, somewhat clean and structured environments. In countries where such environments are not afforded for handicapped people, PWD need to work in rather harsh environments. And robots are meant to help PWD in such environments.

We used Target-Oriented Design (TOD) proposed by Chang and Park[9]. In the previous experiences, TOD has proved itself as an effective and efficient design method for developing a robot arm. In its procedure, described in Fig. 1, it is crucial to define a clear and well-thought-out target, after and according to which all the subsequent design steps are straightforward until field evaluations.

This paper is organized according to TOD procedure as follows: In Section II, the target is defined and task

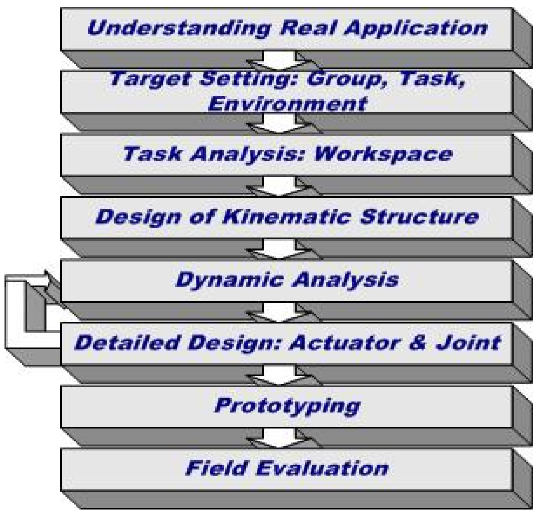

Fig. 1. Target-Oriented Design (TOD) procedure.

points are determined. In Section III, tasks are analyzed. Section IV presents kinematic design using Grid Method, whereas Section V dynamic design including stress analysis. In Section VI detailed design are carried out together with virtual simulation on the defined tasks. The specification for manufactured robot is given in Section VII. Test and field evaluation are fulfilled in Section VIII. In Section IX.we finally make conclusion and mention future activity

2. Target definition

As the first step of robot design, we define the target in terms of a Mission Statement. Essentially, a target consists of three elements: tasks, types of PWD, and environments. The target definition is explicitly articulated in terms of the Mission Statement and is equal to find unknowns, X, Y, Z and With, as described in the upper part of Fig. 2. Note that the types of PWD are represented by X and Y; the task by Z; and the environments by W.

Although simple to formulate, it was difficult to determine X, Y, Z and W. Fortunately, however, it becomes possible to solve for them by incorporating three strategies (or constraints) shown in the lower part of Fig. 2. Each strategy is followed by an obvious question and each question presents the guidelines for subsequent research.

Mission Statement **:**

Develop a Robot Arm that can help PWD of X Type, with Y degree of severity to do Z tasks in W environment

Three Strategies **:**

A. Assist as many PWD as possible.
What kind of PWD takes majority?

B. Take present situation for granted
What do employers want them to do for now?

C. Make robots assist what PWD need
What do PWD want robots to assist?

Fig. 2. Mission Statement and Strategies for Target Definition

Finding the answers to these three questions have taken all our resources for a 13 months. To find out the types of PWD that take the majority in Korea, Strategy A in Fig. 2, we surveyed and analyzed annual reports, statistics and demography about PWD in Korea[17-18]. For Strategy B, we visited KEPAD(Korea Employment Promotion Agency for the Disabled), National Rehabilitation Center, several vocational training schools and more than ten companies such as Mugunghwa Electronics. There we made interview with managers and employers as well as social welfare workers, to get information about the preferences of employers. And for strategy C, we interviewed with PWD working there and made observations of our own.

The answers obtained through the research above may be summarized in three facts:

Physically handicapped people and people with encephalopathy account for 65 percent of all PWD in Korea.

Many of the tasks most employers and managers in Korea want PWD to do are simple and repetitive tasks involving physical strength, such as assembling, packaging, sorting, and simple inspection.

People with upper-limb disabilities are rarely employed because they can hardly perform the tasks in B. In order for this type of PWD to be employed, therefore, robots helping them do fine movements are indispensable and something eagerly longed for.

One more important fact to consider is that to do such tasks is also a part of rehabilitation. Hence, to use fully automated devices, although convenient, may not be very wise for the functionality of their disable parts.

Taking all these facts into account, we have finally determined X, Y, Z and W as the followings. X and Y are *physically handicapped people* who cannot move one arm owing to amputation, or joint disease, or deformation, or peripheral nervous disability. In addition, X and Y include *people with encephalopathy* unable to move one side of the limbs owing to cerebral paralysis, or spastic paralysis whereas they can move freely the other arm and hand. As for Z, robot arm will assist the PWD above to do *circuit test of PCB* and *soldering inspection and repairing of PCB* shown Fig. 3. As for W, we set *a working table with a conveyor line in Mugunghwa Electronics*, where these tasks are carried out. Incidentally, the company employs about one hundred and twenty (about 75% of all the employees) handicapped employees.

In summary, we want to help people with disabilities at one side of their arms to carry out two tasks through the co-work with robot arm, which plays the role of their disabled arm. And the two tasks are ***Circuit test of PCB*** and ***Soldering inspection and repairing of PCB***.

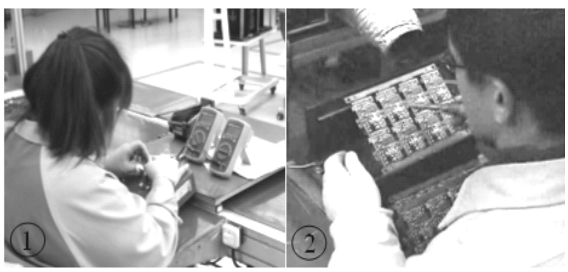

Fig. 3. Defined Tasks: 1. Circuit test of PCB,
2. Soldering inspection and repairing of PCB

3. Task analysis

In order to design a robot arm carrying out predefined tasks, it is necessary to describe tasks quantitatively. We analyzed these two tasks to determine the followings: the type of robot arm, the degree of freedom; the base of robot, task points, task execution time and payload.

The first task, *Circuit test of PCB*, is analyzed to identify the payload to be handled, the sequence of procedures and characteristics of the task. The payload is a PCB with 20g weight and 4×5cm size. This work is carried out according to the following procedures:

· *Proc. 1*. The worker brings a PCB from conveyor.

· *Proc. 2.* The worker puts it down on zig[1] and tests it.

· *Proc. 3.* The worker brings it back to conveyor.

This task, carried out repeatedly and frequently in a day, needs sophisticated hand actions. Therefore it is difficult for PWD to do all the procedures in this task. Hence, we have made PWD do Proc. 1&2 and the robot arm Proc. 3, respectively. It is noteworthy that the robot 'assists' in the sense that it performs some procedures, whereas PWD do different ones.

For the robot arm to carry out Proc. 3 adequately requires its kinematic configuration to be similar to SCARA with an additional two DOF mobility: prismatic motion along the z-axis and rotation about z-axis. The kinematic configuration is shown in the left part of Fig. 4. Considering the width of conveyor and working table, the base of robot must be located at 55cm in the y-direction away from the center of a zig device. Task points defined with respect to the base of robot arm are described in Table 1. Although the task is accomplished in about 5s in the factory, we set task execution time up to 7s because of the safety of handicapped users. Maximum payload including PCB and tool's weight should be limited to less than 700g.

The second task, *Soldering inspection and repairing of PCB*, is analyzed as the following: The payload is a PCB with the weight of 250g and with the size of 16×12cm, while the soldering device weighs about 200g. This task is carried out on the working table in accordance with the following procedures:

· *Proc. 1.* The worker brings a PCB from working table.

· *Proc. 2.* The worker puts it down on PCB holder.

· *Proc. 3.* The worker inspects the soldering state of the PCB, and repairs if it has any defect.

· *Proc. 4.* The worker brings it back to working table.

Repairing a PCB in Proc. 3 is composed of three sub-procedures: 1) sticking electronic parts closely to the surface of PCB if parts are a little off; 2) adding lead to a place where lead is lacked in PCB; and 3) removing lead from a place with faulty connection in PCB. And, we observed that the workers often use their right hands to handle the soldering device, whereas use left hands either to grasp PCB; or sticking an electronic part into it; or to grasp resin-cored solder when applying more lead, or to grasp lead remover when removing. it. So, we designed assisting robot to play a

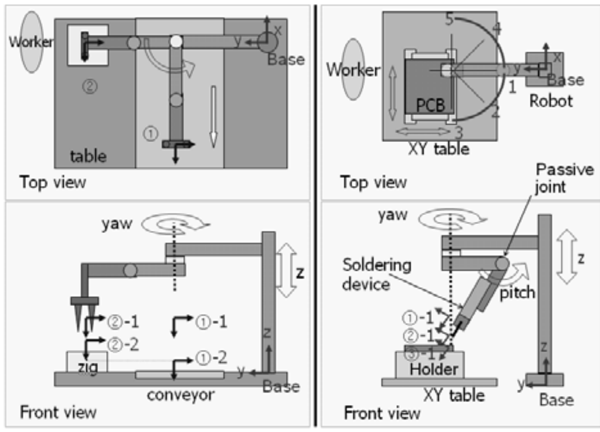

Fig. 4. Schematic diagram of robot arm: Left -Test Circuit test of PCB, Right-Soldering inspection and repairing of PCB.

role of right hand (handling the soldering device), and the handicapped workers to carry out a role of left hand by themselves.

In order for the robot arm to do this, it should be able to adjust the angle of soldering device. Hence it became necessary to add a passive joint to the second link as shown in the right part of Fig. 4. Since the task also needs precise XY positioning of PCB with accuracy of less than 1mm, we designed an XY table to hold PCB

TABLE 1
TASK POINTS FOR TEST WORK ON THE CIRCUIT OF PCB

No.	Location	x	y	z	θ_z	θ_y	θ_x
1	①-1	-30	25	15	180º	0º	90º
2	②-1	0	55	15	90º	0º	90º
3	②-2	0	55	9	90º	0º	90º
4	②-1	0	55	15	90º	0º	90º
5	①-1	-30	25	15	180º	0º	90º
6	①-2	-30	25	2	180º	0º	90º
7	①-1	-30	25	15	180º	0º	90º

Here Z-Y-X Euler angles are used and units are cm and deg.

TABLE 2
SOLDERING INSPECTION AND REPAIRING WORK ON PCB

No.	Location	x	y	z	θ_z	θ_y	θ_x
1	①-1	0	25	25	90º	45º	-90º
2	②-1	0	55	25	0º	45º	-90º
3	②-2	0	55	25	45º	45º	-90º
4	②-3	0	55	25	90º	45º	-90º
5	②-4	0	25	25	135º	45º	-90º
6	②-5	0	25	25	180º	45º	-90º
7	③-1	0	55	25	0º	45º	-90º
8	③-2	0	55	25	45º	45º	-90º
9	③-3	0	25	25	90º	45º	-90º
10	③-4	0	25	25	135º	45º	-90º
11	③-5	0	55	25	180º	45º	-90º
12	①-1	0	55	25	90º	45º	-90º

Here Z-Y-X Euler angles are used and units are cm and deg.

[1] A circuit testing device for PCB

and to adjust the position of PCB easily by one hand. Taking the width of real working tables and the XY table into account, we decided the base of robot to be located on the surface of working table at 35cm in the Y-direction away from the center of XY table. Accordingly, the task points have been determined with respect to the base. Considering real work and safety for PWD, execution time was restricted to about 10sec on repairs. Maximum payload including soldering device is limited to less than 600g.

In summary, through task analyses, we have obtained the shape of robot so that this robot arm can accomplish two predefined tasks, *Circuit test of PCB* and *Soldering inspection and repairing of PCB*, and we determined task points for each task as TABLES 1 and 2.

4. Kinematic design

Kinematic design is to find a geometric structure that realizes the pre-defined task points. To elaborate, we make the union of all the task points in TABLES 1 and 2, to define the *task space* (or *workspace*). Using task space together with predetermined shape and the degree of freedom (DOF), we determine geometric structure in terms of kinematic parameters like Denavit-Hartenberg's notation proposed by Paul[11]: twist angle, link length, link offset and joint angle.

Of several methods capable of kinematic design, we incorporated Grid Method proposed by Park & *et.al*[12]. Grid Method, based on the principle of finite difference method usually used for numerical analysis of heat transfer[13], has shown to be a truly efficient and effective algorithm[14-15] to find optimal DH parameters for a given set of task points.

To find optimal geometric structure suitable to two predefined tasks, it is very important to construct a cost function. We made cost function with performance measures such as equality constraint, desired orientation constraint, obstacle avoidance and limit constraint on link length, offset and twist angle[12]. With respect to the cost function, we carried out optimal kinematic design using Grid Method, and the result is shown in Fig. 5 and Table 3. According to the result, the schematic diagram of robot for each task is described in Fig. 6 with dimensions.

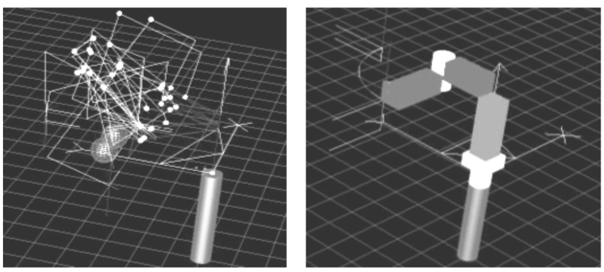

Fig. 5. Kinematic design using Grid Method; Left is initial state before optimization and Right is the result after optimization.

TABLE 3
DH PARAMETERS AFTER OPTIMAL KINEMATIC DESIGN

No.	Joint type	θ	d	l	α
1	Prismatic	90º	38.5	25	0º
2	Revolute	90º	-6	15	90º
3	Revolute	0º	0	14	0º

Here θ, d, l and α indicate joint angle, link offset, link length and twist angle respectively. Units are cm and deg.

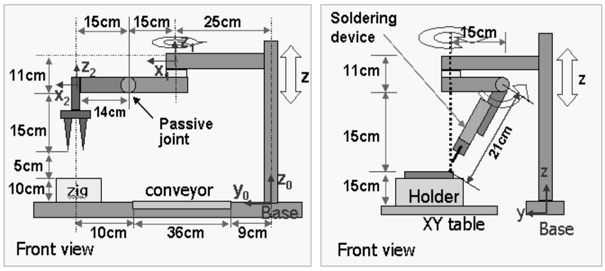

Fig. 6. The Schematic diagram after Kinematic design.

5. Dynamic design

In order to maintain productivity of two predefined tasks, robot arm should be able to move with required speeds for given tasks. To this end, robot arm needs to be made as light as possible and to adopt suitable actuators, by dynamic design process including stress analysis.

We made dynamic design procedure with Solid edge, Nastran[2] and TODP[3] described in Fig. 7. Loop 1 is the process to find out link thickness subject to the safety constraint in terms of stress, when the outer perimeter of the link set to a constant value. Loop 2 is to calculate required torque and velocity and to select proper motor and gear ratio with motor catalog. In this process, payload, friction and motor efficiency should be considered together.

We carried out dynamic design so that safety factor for

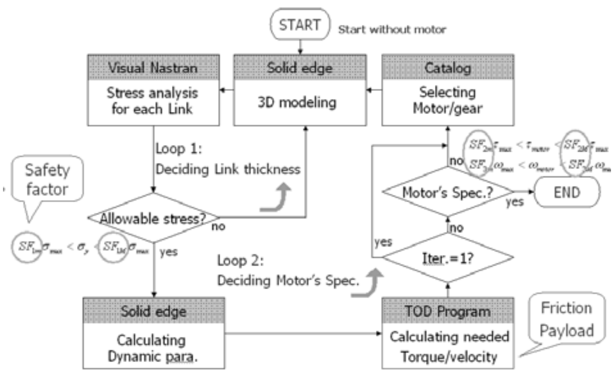

Fig. 7. Dynamic design procedure using Visual Nastran and TODP.

[2] Commercial softwares: Solidedge – 3D design software, Visual Nastran – stress analysis software.

[3] Robot design & simulation software developed by ourselves: functions – kinematic design and kinematic/dynamic simulation of robot manipulators.

maximum stress is more than 3 when using aluminum alloy 1100-H14 of which yield stress is 100MPa, safety factor for maximum torque is more than 2 when considering viscous and coulomb friction and safety factor about maximum velocity has about 1.5. Here payload including gripper weight is 700g and outer size of each link is 5×5cm^2. On considering payload and friction together, torque needed at each joint is 0.480Nm and 5.976Nm. Velocity needed at each joint also is 450rpm and 30rpm. The third joint, designed as a passive joint, is fixed after once setting it up. The final results of *Circuit test of PCB*(faster task than *soldering inspection*) are shown in Fig. 8. The thicknesses of Link 1, 2 and 3 have been determined to be 3mm, 2.5mm and 2.5mm, respectively.

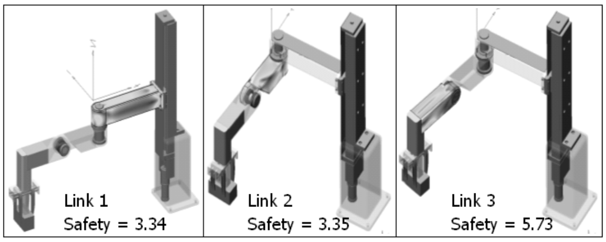

Fig. 8. The results of stress analysis on each link performed with finally determined motor and gear.

6. Detail design and simulation

After determining motor, gear of each joint and thickness of each link through dynamic design, we carried out detailed design. The third joint (a passive joint) is designed so that its angle can be easily adjusted with screw button before starting to work. The third link is designed in such a way that gripper can easily be exchanged for each task.

Robot arm needed two kinds of gripper to assist PWD to do two predefined tasks. The gripper for *Circuit test of PCB*, is designed to be able to hold a PCB with 4×5cm size. On approaching to hold a PCB, it has geometric structure to push Zig(testing tool)'s supporter to outer side, in three directions at once. To set up initial position of gripper according to the change of working environments, it is designed to move 2cm in the y direction and 3cm in the z direction. The gripper for *Soldering inspection and reparing of PCB*, is designed to move about 3cm along the center line of third link to set up initial position.

On *Soldering inspection and repairing of PCB*, XY table (holder for PCB) is necessary for PWD to adjust the position of PCB to repair. It is designed to have a little compliance (about 2mm) when soldering device presses a PCB down for repairs. It is also designed that user can adjust the position of PCB easily by using magnetic force.

After the detailed design and before prototyping, 3D simulation was conducted to confirm whether designed robot arm can fulfill predefined tasks well. The 3D simulation is shown in Fig. 9.

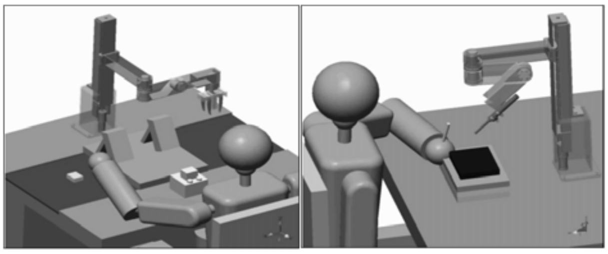

Fig. 9. Evaluation on robot arm through 3D simulation.

7. Prototyping

Owing to the effectiveness of TOD, we could prototype the robot arm in short period without any serious problem. The prototype is shown in Fig. 10. The interface device, shown at right lower part of Fig. 10, has several buttons such as starting button, ending button, left and right button to rotate 2nd joint, mode conversion switch, emergency switch, lamps indicating the current state of a work and foot button used on approaching soldering device to the surface of PCB for repairs. The interface device is used with one hand to operate robot arm to carry out two predefined tasks..

The specification of developed robot arm is shown in Table 4. The controller is designed on the basis of an

Fig. 10. Developed robot arm, XY table and Interface device. the left figure indicates the initial position of robot for *Circuit test of PCB*; and middle figure indicates the initial position of robot for *Soldering inspection and repairing of PCB*. And the right top figure indicates XY table used for the user to find a position for repairs.

TABLE 4
THE SPEC. OF ROBOT ARM IN DESIGN AND AFTER MANUFACTURING

Specifications		Design target Values	Measured Values
Payload (kg)		0.70	1.00
Moving Range	Joint 1 (mm)	300	307
	Joint 2 (deg)	0~270	±270
Maximum Speed	Joint 1 (m/s)	0.10	0.10
	Joint 2 (deg/s)	180	180
Accuracy	Joint 1 (mm)	±0.25	±0.22
	Joint 2 (deg)	±0.50	±0.50
Total Weight (kg)		20.00	19.13

Measured Values are actually measured values in developed robot.

RTAI environment, a PC-based LINUX real time operating system. And Time Delay Control is used for the position tracking control in two predefined tasks [16].

8. Test and Field evaluation

At Mugunghwa Electronics, we tested the robot with 2 PWD, one has physical handicap and the other has encephalopathy. We had them carry out each tasks with the assistance of robot arm as shown in Fig. 11. Afterwards, we made interviews with them and their supervisor about its strengths and shortcomings. Throughout the tests, the robot assisted the PWD to carry often the two tasks quite well, making us convinced that it could be applied before long to actual working places. The response of the supervisor was also positive and encouraging.
But there were three minor criticisms that demanded improvements. The first criticism, which came from the supervisor, points out that in *Circuit test of PCB*, the speed of robot arm was a little slow. The speed was reduced deliberately – task execution time was changed from 5s to 7s – for safety reason. Until the struggle between productivity and safety is over, we better find somewhat a mid-point. The second criticism, from the PWD, was about the difficulty of precisely positioning the soldier in *Soldering inspection and repairing of PCB;* we fixed the problem by using a laser point. The third comment was that PCB on XY table has better be tilted to PWD for easy inspection.

Fig. 11. Field test: 1. Test work on the circuit of PCB,
2. Soldering inspection and repairing work on PCB

9. Conclusion

We have developed a robot arm assisting PWD in work place, in accordance with TOD. The intended PWD are physically handicapped people and people with encephalopathy; the intended tasks and environment are *Circuit test of PCB* and *Soldering inspection and repairing of PCB*, at working table with a conveyor line in Mugunghwa Electronics.

Throughout the field test, we confirmed that the developed robot arm could assist the PWD to do the above two tasks very well, promising imminent application in real work places.
TOD procedure again is effective and efficient. Thanks to elaborate target definition, we could save times and costs in the straightforward design and prototyping procedures.

Acknowledgment

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