Applications of Supernumerary Robotic Limbs to Construction Works: Case Studies

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Abstract

In construction sites, most of manual works require at least two workers cooperating each other to complete a task properly. If it is possible to make a single worker carry out these kinds of tasks with the assistance of a robot, the overall construction efficiency can be increased. This study deals with the application of a supernumerary robotic limb (SRL) to the construction tasks.

In this paper, two typical construction tasks that can be improved by supports of SRL are considered. One includes the tasks that require a worker to hold an object like a panel in a desired position with an appropriate force while the other worker finishes main processes. The other contains moving or holding construction materials which are difficult to be held by one hand not because of its weight but because of its shape or size. For the first case, the SRL that sits on shoulder or waist with position based force controller can be utilized. For the second case, the robotic limb should be able to assist the worker in holding and balancing the object while the one carries it with one hand. As for the case studies, two types of extra robotic limbs were used. One was mounted on the shoulder and the other was attached on the wrist. Both types were applied in the situation of ceiling works in different ways. From many experiments, it was shown that the SRL can be effectively utilized in construction sites for diverse works.

Keywords –

Supernumerary robotic limbs; Wearable robot; Construction work

1 Introduction

There have been much research on the applications of automation and robotics in building construction. Robots can be utilized to substitute human works in a dangerous environment or to increase the construction performance. One way to improve the efficiency of overall construction works is to enable a single worker to complete a task that originally needs two or more workers to collaborate. Most of such manual works in the construction site require at least two people to cooperate each other to complete the job properly. In this case, the main process is usually done by one person and the others perform supporting tasks. Thus, if robots are able to assist the main process autonomously, the manual works can be carried out by one worker and the construction efficiency will be improved.

Various kinds of robots for different purposes have been researched and among them, wearable ones have emerged as one of the promising robots with diverse capabilities. A typical wearable robot is the exoskeleton which is normally used to support human in the aspect of power [1]. Separately with this, a new type of robot named SRL (Supernumerary Robotic Limbs) has been developed [2]. The main difference between the exoskeleton and the SRL is that the SRL have ability to be operated independently of human arms. Therefore, the SRL can be applied to a work that requires multitasking rather than power supporting. With this point, the SRLs are able to help a single worker to perform the main process and supporting tasks simultaneously which will result to improvement in efficiencies of the construction works.

In this study, in order to investigate applicability of the SRL to construction works in terms of multitasking, two different types of SRL were designed and manufactured. As case studies, by conducting many experiments in the assumption that the SRL are applied to assist ceiling work, the performance and feasibility of the SRL will be examined.

2 Case Analysis

Among many construction tasks which are done by two or more people, two typical cases are introduced in this study. The first case includes paneling, ceiling, and pilling works. The common ground of these works is that the main job like drilling or hammering, etc. (jobs for fixing objects in place) is performed by one worker, and the other worker have to hold construction materials such as panels or stake in the desired position and orientation until the main process is completed. By substituting the entire manual holding task with the operation of SRL, a single worker can play a role of two people at the same time. For this purpose, SRL first have to apply forces to the desired point of objects with appropriate magnitudes. In addition, since the base of SRL is attached to the human body, SRL should be able to maintain its contact point and contact force on materials while the worker moves and finish the main process.

The second case is about moving or holding construction materials which are difficult to be held by one hand not because of its weight but because of its shape or size, and thus need to be supported by two hands. If both 2 hands are used only to carry objects, the person is not able to do any other works. However, by making one hand free from holding the material, some simple tasks which are easily dealt with the other hand can be carried out simultaneously, and therefore, multitasking is available. To achieve this objective, the SRL should be able to assist the worker in holding and balancing the building materials such as panels or pipes while the worker moves around or perform other tasks. For each case and corresponding requirements mentioned above, two different types of SRL were applied to actual experiments.

3 Hardware and Control

Specifications of the SRL (such as dimensions, attachment point on human body, or kinds of end-effectors, etc.) are various depending on the practical task in construction site. For instance, the SRL can be installed on waist [2-4] and the end-effectors in arc-shape might be suitable for grabbing stakes in case of the pilling work. If SRL assist panelling or ceiling works, the attachment point of SRL can be on back or shoulders [5], and the end-effectors should be flat, or round shaped to press and hold panels effectively. In this study, two types of SRL for different cases were utilized with intention of examining both types in the situation of ceiling works in separate ways.

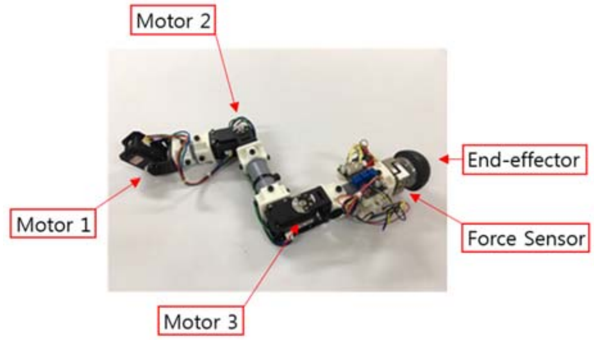

Figure 1. Manipulator structure of SRL for ceiling work

3.1 SRL for Ceiling Work

3.1.1 Hardware Specification

For the first case of applications, SRL with two identical arms are used for ceiling work. The entire SRL is divided into manipulators and shoulder mount (base of limbs) [6, 7]. Figure 1 illustrates the structure of manipulator. The end-effector of the SRL is made of hemisphere-shaped rubber material and it is fixed to the manipulator. The hemisphere structure makes a point-contact possible between the end-effector and panels regardless of posture of the manipulator. Rubber material prevents the contact point from slipping on the panel. Force sensor is connected with end-effector to calculate forces acting on the end-effector in 3-axis. Each manipulator has three motors (three-DOFs) to press panels on the ceiling and to compensate for horizontal movement of the worker while the drilling task is in progress. Shoulder mount which is described in Figure 2 consists of manipulator holder, back holder and vest. An IMU (inertial measurement unit) is attached to one of the manipulator holder to measure rotational movement of human body. Each manipulator is fixed to manipulator holders and two manipulator holders are connected to the 1 back holder by hinge structure to make rotating of the worker in yaw direction comfortable. The back holder is installed on back shoulder of vest and the worker can collaborates with the SRL by wearing the vest [6, 7].

Figure 2. Shoulder mount of SRL for ceiling work

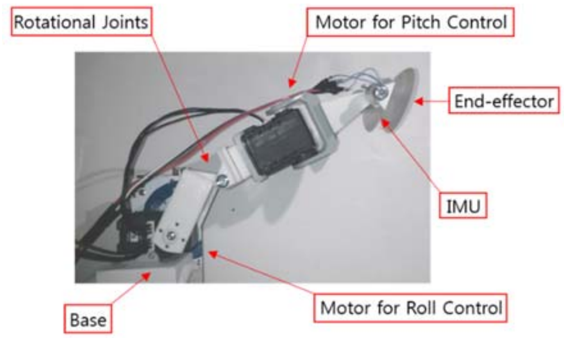

Figure 4. Structure of SRL for holding object

3.1.2 Control Algorithm

To maintain contact point and contact force, position based force controller is applied [8, 9]. Once the end-effector of SRL are set on the desired point of panel, force in Z-direction is controlled first according to preset magnitude to hold the panel stably. After that, force sensors and IMU continuously measure forces in X, Y, Z-directions, roll and pitch. If worker moves during the work, relative position of end-effector with respect to the human body should be adjusted to keep supporting panels. Since values from force sensors and IMU varies depending on translational and rotational movements of the worker, the controller can estimate motion of the worker. Based on these values, the controller calculate required position of the end-effector and required rotation angles of motors to compensate for movement of the worker. According to this process, three motors are regulated by the controller to keep contact point and contact force [6, 7]. Overall algorithm is represented in Figure 3.

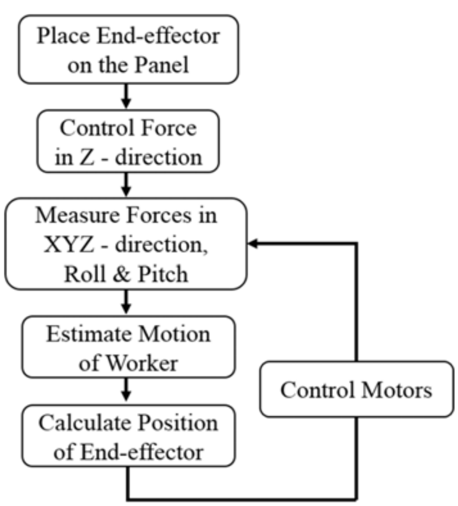

Figure 3. Control algorithm for ceiling work

3.2 SRL for Holding Object

3.2.1 Hardware Specification

For the second case of applications which is for holding or carrying construction materials with one hand, SRL with one arm is applied. Overall structure of the SRL represented in Figure 4 is composed of manipulator and base. The end-effector of SRL which is flat-shaped and covered with rubber is connected to the motor by free rotational joint. Shape of plane makes supporting panels stable and rubber material is used to slips between the end-effector and object. An IMU is installed on the end-effector to measure slopes of the construction material. The number of motors for manipulator was determined according to required number of degrees of freedom. To prevent an object from falling from the hand, roll and pitch of the object should be adjusted, and this account for two motors. A free rotational joint in pitch direction is applied to control elevation of the object effectively and this joint is supported by torsion spring to maintain initial posture of the SRL. When values of roll and pitch change at the same time, it causes change in value of yaw. The value of yaw seems uninfluential to balancing, however, if yaw of the object is varied with respect to human body, it causes twisting and pains at wrist. Therefore, another free rotational joint in yaw direction is adopted between two motors not to make changes in yaw apply uncomfortable forces to wrist of the worker. Manipulator is assembled with the base and the base can be fixed on wrist or forearm by band. Consequently, SRL is attached on human body when it operates and it is illustrated in Figure 5.

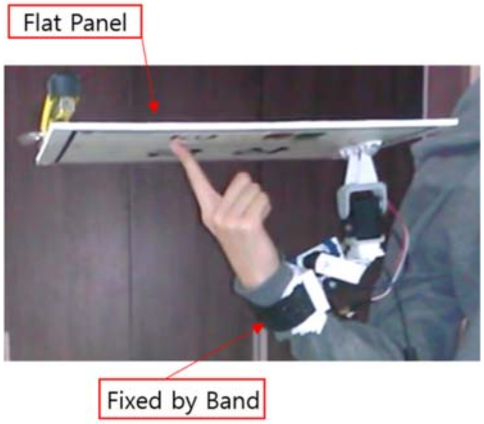

Figure 5. SRL for holding object in operation

3.2.2 Control Algorithm

During the work, construction material is held by two contact areas which are divided into approximately. One is between the SRL and the object. The other is made between hand of the worker and the object. Position and orientation of the former is regulated autonomously by the SRL, and therefore, overall balance of the material is maintained. Figure 6 shows control algorithm of the SRL. Once it starts operating, values of roll and pitch of the object are measured. If the object is inclined a lot to certain direction, it is easy to be dropped since it is not fixed to the hand or SRL. Hence, angular velocities of motors have to be large enough to avoid fall of the object. On the other hand, if slope of the object is small, the angular velocities of motors should be rather small to prevent the object from moving by its inertia near almost stable position. Based on this, the controller determines the velocities of motors which is proportional to the values of IMU. According to this process, motors are regulated to balance the object and to make both roll and pitch values become zero.

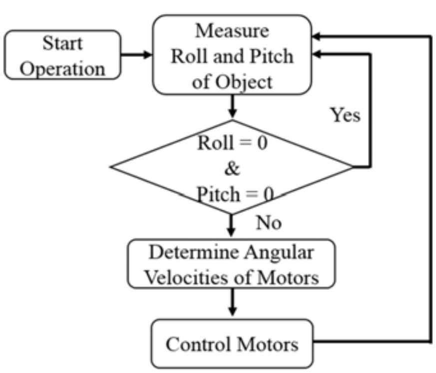

Figure 6. Control algorithm for holding object

4 Experiment

Among various kinds of task to which the SRL can be applied, ceiling work was selected as a task to be carried out in experiment to verify performance of the SRL. The SRL for holding object as well as SRL for ceiling work was examined in situation of the ceiling work in a way of holding panels with one hand.

4.1 SRL for Ceiling Work

The most important performance for this type of SRL is ability to support panels until drilling work is finished. Therefore, maintaining contact force and contact point between the end-effector and object should be verified while a worker who wears the SRL moves. For this purpose, position and forces of the end-effector were measured in the experiment. The end-effector was placed on certain point of structure for experiment, and contacting force was regulated. The person then made translational movements in directions of three-axis and rotational movements as indicated in Figure 7. Measured displacement of the end-effector and forces according to the position of the end-effector are described in Figure 8, and Figure 9 respectively. From the results, it was observed that compared to position change of human, which was approximately 170mm in maximum, position change of the end-effector was less than 20mm which is small enough to maintain contact point, and contacting forces in each axis were also maintained. After that, separately from the measurement experiment, the ceiling work process which imitated the actual tasks in construction site was performed successively.

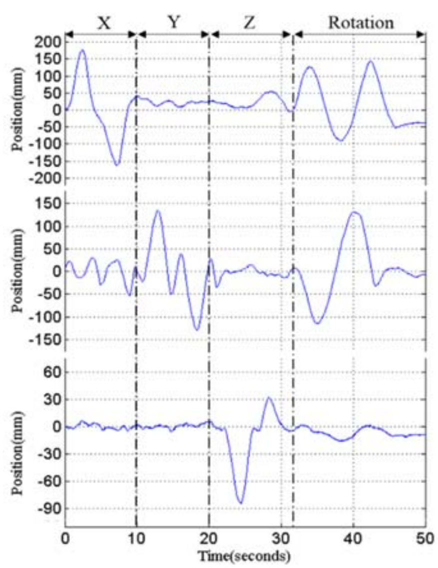

Figure 7. Input movement of person

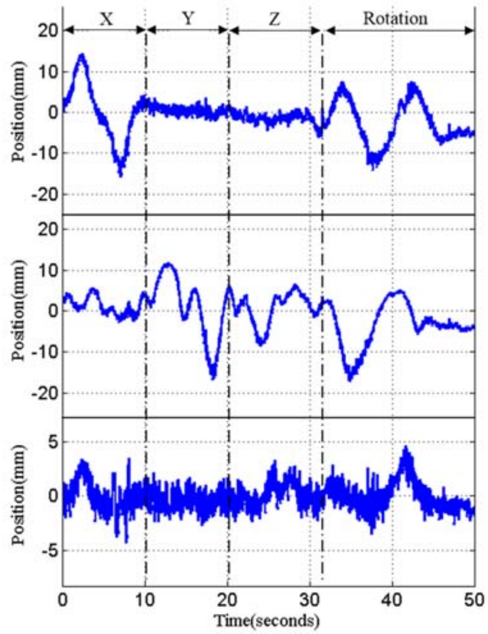

Figure 8. Output movement of end-effector

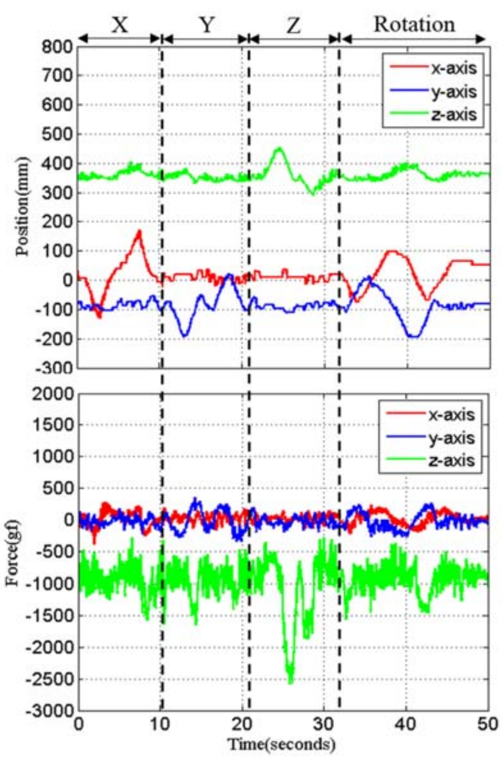

Figure 9. Force data according to position of end-effector

4.2 SRL for Holding Object

The main performance of SRL for holding object is making a worker be able to hold or carry construction materials with one hand. Accordingly, the ability to balance an object should be demonstrated. In the experiment, a flat panel was placed on the SRL. After that, input slope angle which would have been angle of the panel if SRL had not work was given in terms of roll and pitch angle separately. The result output roll and pitch angles which were compensated by the SRL are represented in Figure 10, and Figure 11 respectively. From the experiment result, it was examined that input angle up to 30 degrees in which the object is easy to fall can be reduced to output angle of 5 degrees stably. To verify performance of supporting object in situation similar to actual work environment (worker proceeds certain task with the other hand), ceiling work was carried out with his SRL. In this case, the task was proceeded in a way of completing the ceiling work by holding panel by one hand with assist of SRL, and conducting drilling with the other hand.

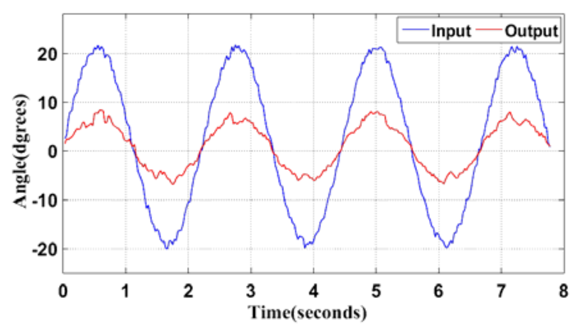

Figure 10. Input and output roll angle

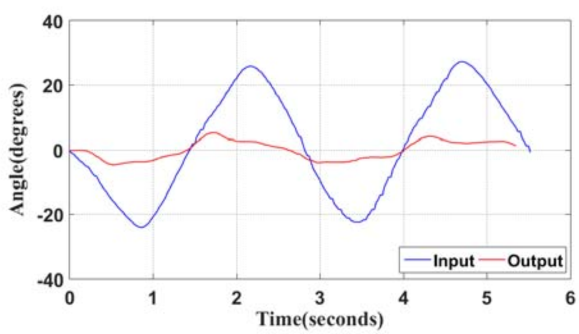

Figure 11. Input and output pitch angle

5 Conclusion

This study suggests ways to apply new type of wearable robot which is called Supernumerary Robotic Limbs (SRL) to construction works. From the fact that most of manual construction works require collaboration of more than two workers, the study focus on one of the advantages of the SRL that it can operate independently of human limbs. By making use of this point, substituting supports of additional workers with operation of SRL can be achieved, and therefore, some kind of works are able to be dealt with by one person or one person becomes able to handle several tasks simultaneously, which result to improvement in efficiency. As specific kind of works, ceiling work, and holding or carrying construction material with one hand were selected. Two different types of SRL were utilized for each case. Experiments were conducted to verify performances of the SRL, and ceiling works were carried out according to the procedure of practical ceiling work. From many experiments, it was demonstrated that Supernumerary Robotic Limbs can be effectively utilized in construction site for diverse works.

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