Design and Application of a Wire-Driven Bidirectional Telescopic Mechanism for Workspace Expansion with a Focus on Shipbuilding Tasks

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Abstract
Various products and patents have been established with regard to telescopic mechanisms over a long period of time. However, to the best of our knowledge, with reference to motional characteristics, few studies have been reported on a telescopic mechanism that is capable of bidirectional extension. Moreover, as we wish to point out here, such a kind of mechanism has received little attention due to the absence of practical applications. However, in the case of blast-cleaning and painting in double-hulled structures in shipbuilding, the bidirectional-extension mechanism seems to be a worthwhile subject for investigation since it will be of great help in the execution of suggested tasks for the entire transverse web floor with a range of 2–3 m. Since the self-traveling robotic platform is located on longitudinal stiffeners whose heights range from 400 to 800 mm, the manipulator to be installed on the robotic platform should have a bidirectional stroke to continuously approach the upper and lower sections of the transverse web floor. Further, with the rapid progress of the shipbuilding industry in South Korea, the importance of the bidirectional-extension mechanism in the automation of double-hulled structures has been increasingly recognized. Thus, for the design of a new mechanism, this paper describes a new type of telescopic mechanism that is capable of bidirectional strokes; the paper focuses on the mechanical design, analysis, manufacture and experimentation. Further, a customized pulley with a cylindrical-helix groove is designed to prevent the problem of overlapping steel wires since it leads to inaccurate position control with respect to the motor’s rotation. In particular, experiments have been conducted in terms of the positional repeatability of the manufactured telescopic manipulator and the quality of blast-cleaning of an upper section of a transverse web floor in a double-hulled structure. Throughout the experiments, the manufactured mechanism has demonstrated an amazing bidirectional translating stroke that has ranged from −500 to +2000 mm in field testing. Further, the repeatability of the manufactured bidirectional manipulator with the suggested motor–pulley system has been clearly identified as ±0.84 mm in the descending direction and ±0.63 mm in the ascending direction.


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1. Introduction

In the case of accidents, e.g., the Exxon Valdez oil spill of 1989 [1], involving commercial ships that carry liquid cargo, such as liquefied natural gas, liquefied petroleum gas and crude oil, serious environmental damage can be caused to the ocean. In an attempt to minimize this, vessels such as very large crude oil carriers, bulk carriers and liquefied natural gas carriers incorporate double-hulled ship walls, as shown in Fig. 1. These consist of outer and inner walls that are spaced 2–3 m apart. If the outer wall is holed as a result of a collision or stranding, for example, the inner wall can still prevent the outflow of liquid cargo [2, 3].

However, the manufacture of double-hulled ships is more time-consuming and expensive than that of single-hulled vessels. The major cause of this is possibly that efficient robot-based automation with regard to blast-cleaning, painting and welding in the enclosed structure is quite difficult and slow due to the narrow access hole (600 × 800 mm) and the confined space in light of the multiple existing stiffeners (the access hole can be used to place the robotic system inside the enclosed structure). In the case of welding tasks in double-hulled structures, only bottom-side welding along the contacting boundary of the open block and the bottom shell is required. However, other tasks, such as blast-cleaning and painting, should be done for the entire surface of the transverse web floor all at once. That is one of the reasons that such tasks in double-hulled structures suffer from slow speed in automation. Consequently, the strokes for the robotic manipulators lengthen for the large workspace in spite of efforts to minimize the mechanical size owing to the narrow size of the access hole.

Figure 1. Overall view of the double-hulled structure in the shipbuilding industry.
The required degrees of freedom (d.o.f.) in blast-cleaning and painting consist of 3 positional d.o.f. and 2 orientational d.o.f. Typically, in order to expand the workspace in the upper direction with respect to the robot’s base frame, the addition of a positional d.o.f. may be a solution in such cases. In other words, the positional d.o.f. makes it possible for the end-effector of the manipulator to approach the upper section of the transverse web floor. However, the addition of axes unfortunately increases the mechanical size and weight of the mobile platform, manipulator and embedded controller; it also has some adverse consequences for the embedded controller, e.g., electric noise from the increased wiring.

For the above reasons, if continuous bidirectional translation along the height with respect to the robot’s base frame is possible in spite of no enlargement of the machine size and no additional d.o.f., it will be important in some fields, e.g., shipbuilding, construction, rescue, mining, etc. Those fields may feature narrow and confined spaces in certain tasks. In particular, the double-hulled blocks represent quite a hazardous environment for workers, as shown in Fig. 1. The paper describes its contribution (and originality thereof) to the design of a bidirectional telescopic mechanism; it also demonstrates the performance of the mechanism in terms of the measurement of repeatability and the application of the manufactured mechanism to the blast-cleaning task in double-hulled structures.

2. Telescopic Mechanism

From the point of view of expansionary mechanisms, telescoping in mechanics describes the movement of one part that slides out from another, lengthening an object from its rest state. That is, it can be defined as a multi-stage system that is capable of unidirectional and adjustable strokes. As shown in Fig. 2, the telescopic mechanism is designed with a series of tubes having progressively smaller diameters and nested within each other. The largest-sized tube is called the main or barrel. The smaller inner tubes are called stages. The smallest stage is typically called the plunger. This telescopic mechanism has a practical design limit as stability becomes more problematic as the number of stages increases.

As mentioned above, existing telescopic mechanisms can be defined as multi-stage systems, which provide more reach in various directions through the collapse
and extension of an object. Thus, the structural characteristics of telescopic mechanisms have been considered to be an important subject. In fact, they have led to various applications in modern equipment. For instance, Fig. 3a shows telescopic cylinders that are actuated by hydraulics for lifting a bridge up and down. Figure 3b shows a telescopic mast system that is elevated by an electric motor with steel wires for land surveillance and reconnaissance vehicles. Figure 3c shows a telescopic ladder system that also is elevated by an electric motor and steel cables for a fire department ladder truck to extend to the upper reaches of an apartment fire.

As shown in Fig. 3a, telescopic cylinders are typically actuated by hydraulics, but some light-duty designs are actuated by compressed air. Hydraulic telescopic mechanisms typically can be classified into two types: single-acting and double-acting. The single-acting type can be extended using hydraulic power, but retracted using external loads. However, in contrast to the single-acting type, double-acting cylinders can extend and retract in both directions. Thus, despite its complexity and expensiveness in relation to the single-acting type, the double-acting type has been used in many kinds of applications, e.g., garbage trucks, transfer trailers, excavator shovels and roll-on/roll-off trucks. However, it cannot be considered that this type of telescopic system is suitable in mobile robotic systems for automation in narrow and confined structures. Some mechanical needs in hydraulic telescopic mechanisms, such as piping for transmitting the oil pressure and safety devices for preventing accidental discharge due to high pressure, enlarge these types of telescopic system. That is why the double-acting type is not considered by us even though it has great performance compared to pneumatic and electric systems in terms of high positional accuracy, fast system response, and high force and torque with comparatively compact motors.
In Fig. 3b and c, the electric motor power also allows a much greater ladder length to be achieved through the driving of the steel cables. However, in the wire-driven mechanism, positional control is not possible in descent, only in elevation. Moreover, this mechanism also has poor positional accuracy owing to the overlap of cables on the pulley or winch. Based on the above observations, the telescopic mechanism allows a much greater extension to be achieved with a comparatively small mechanical size. Hence, the existing telescopic mechanisms, e.g., telescopic ladders, boom cranes, tripod bases for cameras, risers, etc., have been used in numerous applications by being mounted in machinery through pivot mounts that are welded to one end or the outer body of a barrel. However, it must be noted that existing mechanisms do not enable either bidirectional extension with respect to the mount or accurate positional control, particularly in the case of an electric motor and cable system.

Thus, in order to make good use of the merits of the existing telescopic mechanisms, this paper describes a new design of a telescopic mechanism, which enables bidirectional strokes with respect to the base frame of machinery, with the base being on the electric motor and wire system. Further, the design of a cylindrical-helix pulley, which can settle the problem of inaccurate positional control through duplicate winding in the pulley, is also described. In the section on experimentation and validation, an assessment in terms of the positional repeatability of the manufactured mechanism also will be described to identify the feasibility of application in the field of robotic manipulators.

3. Structure of the Bidirectional Mechanism

Figure 4 shows a schematic configuration of the wire-driven bidirectional telescopic mechanism that is the new mechanism we propose. Figure 4 shows an example of a composition of five stages and three steel wires (a, b and c) actuated by one servo motor. A ‘driven-wire’ (d) is also connected to the servo motor assembly that is orthogonally installed on the back of the base stage, i.e., the first stage. Further, its driving direction can be changed by a motor’s rotating direction. In general the

![Figure 4. Schematic configuration and isometric view of the wire-driven bidirectional telescopic mechanism with five stages.](image-url)
mechanism consists of \((n - 2)\) steel wires and one ‘driven-wire’ for \((n)\) stages and one servo motor for actuation.

The \((n)\) stages are composed of \((n - 2)\) stages, a barrel and a plunger. A passive roller and wire fixtures are attached to each stage; they help to transmit the driving force and fix the wires to the bottom side of the stage, respectively. The servo motor assembly is composed of an AC servo motor with an absolute encoder, a harmonic drive system as a reduction gear and a pulley with a cylindrical-helix groove for preventing inaccurate positional control. The steel wires indicated as a, b and c bind consecutive stages to each other; we term them ‘binding-wires’.

Figure 5 shows a cross-sectional view of the assembled multi-stage system, whose rectangular shape opens at the front side given the bidirectional translation of the plunger. It is difficult to utilize conventional systems of mechanical guidance, such as an LM guide, single-edge slide system, etc., to implement the linear slide of stages for the entire travel distance. However, through sliding dovetail joints in spaces between the stages, mechanical guidance has been achieved. The two sliding boards are commonly of different materials, such as copper and steel, so that the two components can slide together easily with less lubrication on the contacting faces. From the point of view of ‘rope and pulley systems’, one should note that the first binding wire restricts the first and third stages around the first passive roller. Thus, these two stages are considered a single movable pulley system; the rest of the binding wires function similarly. That is, the system can be defined as a compound pulley system.

It was difficult to either employ or discard the conventional design of telescopic mechanisms to achieve bidirectional translation. As shown in the left side of Fig. 6, in the case of a conventional telescopic ladder, the intermediate stages represent the possibility of running down irrespective of the travel distance of the motor–pulley due to the absence of binding-wires. That is, the relative distances between stages cannot be controlled in terms of the rotational angle, \(\theta\), of the servo motor system. It may be possible that the binding-wires, as shown in the right side of Fig. 6, can be combined to prevent the above problems; however, that would increase the complexity of the mechanical design. Thus, by the use of just one control-wire to adjust the travel distance of only the second stage, as well as several binding-wires
for simultaneously restricting relative travel between the remaining stages, linear motion control is achieved in the two directions.

One point remains to be clarified. The last stage has a comparatively short length compared to the rest of the stages. The merit of this design is that it enables bidirectional translation along the whole length of the fourth stage in substance. If the last stage has the same length as the rest of the stages, the practical bidirectional strokes of the end-effector that is to be installed on the last stage no longer exist. In other words, the length of the end-effectors, $l_{w,i}$, should be shorter than that of the last stage and it should have an extra space between the end-effector and either the bottom or top side of the last stage; this may lead to collision with the existing structure. That is why the mechanism cannot provide ‘practical’ bidirectional strokes if the last stage has the same length as the rest of the stages.

4. Motion Characteristics

4.1. Problem Definition

As mentioned earlier, in a conventional pulley–rope system, wires that may be overlapped and irregularly wound on the pulley are believed to cause inaccurate position control and unexpected descent that is accompanied by an impact in terms of the rotational angle, $\theta$, of the servo motor. Figure 7 shows a schematic diagram of the side and front views of some patterns of wire that lie upon other wires. This pattern should produce the undesired radius term, $\Delta \rho$, which would definitely lead to positional error in the directions of translation.

For the purpose of error estimation, the positional error can be interpreted as the difference between the true and nominal positional values. The value of the positional error due to the undesired radius term, $\Delta \rho$, which is the radius increment caused by the previously wound wires, is given by:

$$\varepsilon = \frac{1}{n} \cdot \int_{I} \Delta \rho \, d\theta,$$

where $I$ denotes the radial interval of the rotational angle and $n$ denotes the reduction gear ratio of the harmonic drive system. The integral term, which is the extra wound wire length due to the wires lying beneath the current layer, denotes the po-
sition error with respect to the pulley rotation angle. The error with respect to the motor rotation angle is given by dividing by \( n \).

As an example of the position error for a typical pulley–rope system, first, let us assume \( \Delta \rho \) is a constant value (3 mm) over the rotation of the pulley for (1). Let us also assume that the rotational angle of the pulley is \( 2\pi \) (360°), the radius of the pulley is 34.4 mm and the radius of the driving-wire is 3 mm. Then, the value of the positional error, \( \varepsilon \), can be calculated as approximately 18.84 mm per revolution. Thus, it should be noted that the irregular winding of the wires should be addressed for the application of the proposed mechanism to a robotic manipulator, which requires a relatively high positional accuracy. Thus, by use of a customized pulley that has a groove with the profile of a cylindrical helix as shown in Fig. 8, the linear winding length in terms of the rotational angle is embodied in the proposed mechanical system.

Suppose that the position of a particle on the cylindrical-helix curve in Cartesian coordinate space is given by:

\[
p(\theta') = \begin{bmatrix} x(\theta') \\ y(\theta') \\ z(\theta') \end{bmatrix} = \begin{bmatrix} r \cos \theta' \\ r \sin \theta' \\ h\theta' \end{bmatrix},
\]

(2)

where \( \theta' \) also is equal to ‘\( n^{-1} \times \theta \)’ and is interpreted as the rotational angle of the designed pulley that corresponds to \( n \). Then, in order to compute the arc length, i.e., the distance traveled by the particle, let the vector function be such that \( p(\theta') = [f(\theta'), g(\theta'), h(\theta')]^T \), which represents the positional function of the particle. In an
infinitesimal angular interval from $\theta'$ to $\theta' + \Delta \theta'$, the particle essentially travels in a straight line. The traveled distance is defined as:

$$ |p(\theta' + d\theta') - p(\theta')| = p'(\theta') d\theta' = \left[ \begin{array}{c} f'(\theta') \, d\theta' \\ g'(\theta') \, d\theta' \\ h'(\theta') \, d\theta' \end{array} \right]. $$

(3)

From (3), the travel velocity of the particle on the cylindrical-helix curve for the trajectory, $p'(\theta')$, can be defined as:

$$ p'(\theta') = \sqrt{[f(\theta')]^2 + [g(\theta')]^2 + [h(\theta')]^2}. $$

(4)

As a consequence, for the given interval, $I \subset \mathbb{R}$, the traveled distance, $s$, with respect to the rotational angle of $\theta'$ is then calculated from:

$$ s = \int_{I} p'(\theta') \, d\theta' = \int_{I} \sqrt{[f(\theta')]^2 + [g(\theta')]^2 + [h(\theta')]^2} \, d\theta. $$

(5)

For characterizing the motion of the cylindrical-helix pulley, the distance traveled and the travel velocity has been clarified with respect to the rotational angle of the pulley in (4) and (5).

As mentioned earlier, and as shown in Figs 9 and 10, the $n$ stages are connected to each other through the $(n - 2)$ binding-wires. Thus, it can be clarified that the relative travel distances between the $i$th and $(i + 1)$th stages (for all $i$) are equal to $s$ and the absolute travel distance, $P_{i}$, with respect to the robot’s base frame is given by:

$$ P_{i} \bigg|_{i=1}^{n} = (i - 1) \times \int_{I} \sqrt{[f(\theta')]^2 + [g(\theta')]^2 + [h(\theta')]^2} \, d\theta, $$

(6)

where $n$ is the number of stages (five in the present case).

**Figure 9.** Schematic diagram of the descending motion and absolute strokes of each stage with respect to the base frame.
Typically, the overlapped length of stages in telescopic cylinders is 20–40% of the fully extended length, depending on the number of stages [6]. It should also be clarified that the ratio of the bidirectional strokes in the \( z \) and \( -z \) directions can be determined according to the relative position of the last (fifth) stage from the penultimate stage. In the blast-cleaning and painting tasks for the double-hulled structure of ships, the upper workspace is larger than lower workspace. Thus, the ratio between the upper and lower travel distances is 4:1.

4.2. Velocity Control Scheme

As discussed above, the suggested bidirectional mechanism is designed in the gravitational condition. Hence, it is possible to control the ascending motion through the driving-wire according to the motor’s velocity and acceleration profiles. However, the reader should note that the mechanism cannot be realized in the case of descending motion since it is more dependent on time and gravity. That is, the maximum acceleration that can be obtained would be smaller than ‘free-fall motion’. Such descent can be considered as the ‘free-fall motion with friction’ of a multi-stage system along a straight line with a constant acceleration of \( g \) and friction force \( F_\mu \).

It should be noted that since the friction force is caused by the friction between the sliding stages it should be validated through experiments rather than analytical approaches. In Section 5.2, experiment results show that the friction loss is acceptable for this case. In addition, the equations of motion are represented as:

\[
v_{-z} = f(g, F_\mu, t) = v_{-z,0} - g \cdot t + F_\mu \cdot t
\]

\[
s = g(g, F_\mu, t) = s_0 + v_{z,0} + \frac{1}{2} g \cdot t^2 - F_\mu \cdot t^2,
\]

where \( g \) denotes the gravitational acceleration, \( F_\mu \) denotes friction force and \( t \) denotes the duration of falling.

Due to this characteristic of the proposed mechanism, i.e., it cannot reinforce movement in the gravity direction, the manipulator will not be able to take action against external forces acting in the opposite direction of the gravity exceeding its own inertia. In such cases, although the desired position of the end-effector would
not be obtained, it does not necessarily mean damage to the manipulator since the stages are free to move in the opposite direction to gravity. The stiffness against external forces in the direction of gravity depends on the stiffness of the wire and in all other directions depends on the mechanical stiffness of the manipulator.

The end-effector that is to be installed at the last stage will accelerate in a gravitational field at the same rate, regardless of the mass of the multi-stage system. The required blast-cleaning speed in the field tasks is over 1.5 m/min. Let us suppose that the robotic blast-cleaning speed is set to 4.0 m/min. Then, the required time for accelerating to the rated velocity is approximately 600 ms. The required times for acceleration and deceleration in the motion for most industrial tasks are over 100 ms in light of the inertia of the external load. It should be noted here that the developed bidirectional telescopic mechanism will be suitable if the required time for acceleration exceeds 300 ms. For instance, rapid ascent and descent are not needed in robotic blast-cleaning, which only requires a continuous translating motion in the z direction away from the upper part of the transverse plate. Also, for this reason the springiness of the wire is assumed to be negligible when the required motion is not rapid since the movement of the manipulator will be more as a static system than a dynamic system. These results can be rationalized by experiments on actual blast-cleaning through a combination of a three-axis end-effector for blasting and the self-traveling platform RRX [4].

5. Manufacture and Experiments

5.1. Results on Manufacturing for Autonomous Blast-Cleaning

We have extended the present study of bidirectional multi-stages to particularly cover blast-cleaning tasks in the double-hulled blocks of ships. As a result, the manufactured bidirectional multi-stage, three-axis ‘blasting manipulator’ and six-axis ‘RRX mobile platform’ are represented in Fig. 11. The RRX mobile platform developed in this project has already been established; its self-traveling performance in a field test of shipbuilding has been demonstrated over a year [4]. Further, a

Figure 11. Assembly of the bidirectional ladder and the RRX mobile platform.
customized three-axis ‘blasting manipulator’ is attached to the last stage of the bidirectional multi-stage.

The right-hand side of Fig. 11 represents the result of an assembly of an 11-axis RRX mobile robotic platform and a five-axis blasting manipulator. In addition, the top side of the RRX mobile platform has two LM rails and one rack for an interface with the bidirectional multi-stage system; it serves as a prismatic axis in the y direction on the mobile platform.

The trial performance of bidirectional translation in the assembly plant is shown in Fig. 12. The translation ranged from $-500$ to $+2000$ mm; the reason for the differential stroke ratios for the upper and lower travel distances has already been described in Section 4. As a result of this trial, the bidirectional translation with respect to the base frame has been demonstrated to be useful for other types of tasks. Further, as shown in the right-hand side of Fig. 12, the dovetail joints are used to implement the sliding motion between stages, which represent quite narrow spaces.

5.2. Measurement of Repeatability

The systematic errors can be defined as errors that produce results that differ significantly from the true value by a fixed amount. They may occur due to mechanical misalignments, backlash, fatal defects in the design, etc. Under identical conditions, it has been widely known that systematic errors are easier to detect and reappear more often than random errors since their values are constant in a series of repetitions of the same experiment or observation [5]. Thus, the systematic error is often defined as the expected value of the overall error. Moreover, in contrast with random errors, it is also known that systematic errors can be removed through calibration techniques using a measurement instrument, such as a laser tracker [6]. In the case of a system with multiple d.o.f., the systematic error is bound up with the repeatability rather than positional accuracy. Thus, precision can be greatly improved using calibration techniques if the repeatability is within the desired range. That is, even though the absolute positional accuracy, excepting the random error, is out of the desired range [7–9]. That is, in the case of manufacturing, it can be expected that the
costs will greatly decrease if only the repeatability, but not the positional accuracy is increased [10].

Based on the facts clarified so far, it has been decided to measure the repeatability as an assessment of the manufactured system for examining the possibilities of the application to robotic manipulators. As shown in Fig. 13, in order to measure the repeatability of the translation in the $z$ direction, the experimental environment is organized as follows: the laser tracker system, test-bed and bidirectional multi-stage system. For this purpose, a reflector is attached to the last stage in order to receive the laser beam that is emitted from the laser tracker, as shown in Fig. 13. Through the installed reflector, the laser tracker system of the Leica AT901-B model can continuously measure the three-dimensional position coordinates in space. The measurement methodology of ‘KS B ISO 230-2’ has been strictly observed [11].

The positions of the reflector installed on the bottom side of the last stage are measured for every 250 mm over the entire travel distance with a range of $-500$ to $+2000$ mm and a velocity of 4 m/min. The required time for acceleration was 500 ms, and the data for the first position and last position were neglected.

The experiment was repeated 5 times in order to measure the positions of the reflector according to the directions of ‘KS B ISO 230-2’. As a result, the forward and backward repeatability were obtained from (9) and (10). From the result of the measurement results of unidirectional repeatability in Fig. 14, the obtained values of repeatability are ±0.84 mm in the descending direction and ±0.63 mm in the ascending direction [12].
It should be emphasized here that the manufactured bidirectional telescopic manipulator satisfies the claimed repeatability value of ±5.0 mm [12] in the blast-cleaning task as per the performance evaluation. The reason why the suggested and established positional repeatability of ±5.0 mm is enough in blast-cleaning is that this type of operation may be performed by spraying grit onto the surface. Thus, for the purpose of verification and recognition, the experiment has been carried out as shown in Fig. 15. The reported results on the blast-cleaning of the upper sections of the longitudinal stiffeners pertain to driving in the longitudinal direction. As a result of this experiment, the standard index of the surface roughness value of ‘Sa 2.0’ was obtained at a velocity of 1.5 m/min; it represents the required quality of blast-cleaning and the function of automated blast-cleaning in double-hulled structures.

6. Conclusions

In this paper, a bidirectional telescopic mechanism has been investigated from the perspective of shipbuilding tasks, especially blast-cleaning and painting in double-hulled structures; although there were research reports on inflatable structures for
painting in tight spaces [13], cable-driven manipulators [14] and cable-driven robots for shipbuilding [15], no literature exists on such a mechanism.

The manufactured mechanism has demonstrated an amazing bidirectional translating stroke that has ranged from $-500$ to $+2000$ mm in field testing.

On the other hand, one of the most critical issues in the case of wire-driven telescopic mechanisms has been considered to be the poor positional accuracy owing to the possibility of the duplicate winding of wires on the pulley. Hence, in order to address this problem for application to a robotic manipulator through improved positional accuracy, a cylindrical-helix pulley has been suggested. Further, through the measurement of the positional accuracy using a laser tracker system, the repeatability of the manufactured bidirectional manipulator with the suggested motor–pulley system has been clearly identified as $\pm 0.84$ mm in the descending direction and $\pm 0.63$ mm in the ascending direction. These results definitely demonstrate the usefulness of the proposed bidirectional mechanism for application to robotic manipulators with a focus on shipbuilding tasks.

Finally, actual experiments on blast cleaning have been successfully conducted in the double-hulled structure through a combination of the bidirectional telescopic mechanism, three-axis blasting manipulator and RRX mobile platform. Hence, from the facts clarified so far, it is expected that the developed bidirectional mechanism will definitely find application in construction, rescue operations, etc., where manipulators have to operate in confined and narrow spaces.

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