2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Development of Novel Multifunctional Robotic Crawler for Inspection of Hanger Cables in Suspension Bridges

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Abstract— **This paper introduces a novel robot which is able to climb hanger cables of long span suspension bridges. The robot has been developed for inspection purpose, and it can help us remotely inspect the state of cables by using cameras and Non-Destructive Testing (NDT) devices. The robot consists of two traction modules, two sub modules, and an adhesion mechanism. The unique design of the traction module ensures the stable movement of the robot on the twisted surface of the hanger cable. In this paper, we describe the structure and environmental situation of hanger cables and the mechanisms of the robot. Also, the results of experiments in the indoor and outdoor environments are included.**

I. INTRODUCTION

The maintenance of hanger cables has been a critical issue with the aging of suspension bridges. The visual inspection by a human is currently prevailing for the inspection of hanger cables. However, it is very dangerous and hard for the workers to access every position of a hanger cable because hanger cables are hung at main cable of very high altitude. In addition, it is required to inspect inside as well as outside state of a hanger cable for its accurate diagnosis. Non-Destructive Testing (NDT) is usually used for the inspection on the inside state. It is difficult and dangerous for a human to transport a NDT device because NDT devices are commonly heavy. Therefore, the development of a cable climbing robot capable of transporting NDT devices in place of a human is needed.

In these days, various climbing robots have been reported. The gripper driven climbing robots using the electric motor and the hydraulic pressure were developed [1], [2]. A gripper driven climbing robot is able to move to bent object or to other object from original position but its climbing speed is too slow because there exists a lot of the operation steps only for one motion. The climbing robot which employs the negative pressure generated by the impeller as a method of making the adhesion force was introduced [3]. The robot is able to drive and rotate fast since it is driven by two independent wheels and a ball castor. Although the robot could be driven on a wall with stable adhesion force, it may be fallen from hanger cable because the adhesion force generated by negative pressure is unstable on the curved surface. The robots using the magnetic force were reported [4], [5]. The magnetic-based climbing robots are possible to drive on the pipe of large radius but these kinds of the robots are limited to wide object made by ferromagnetic substance. Also, the robots which are driven by wheels and adhered by springs were developed [6], [7]. In case of using the springs to generate adhesion force, the adhesion force control is not required since the elastic restoring force of the spring is passively generated. Comparing with the gripper-driven robot, the moving speed of the wheel-driven robot is pretty fast, but their payload is not large enough.

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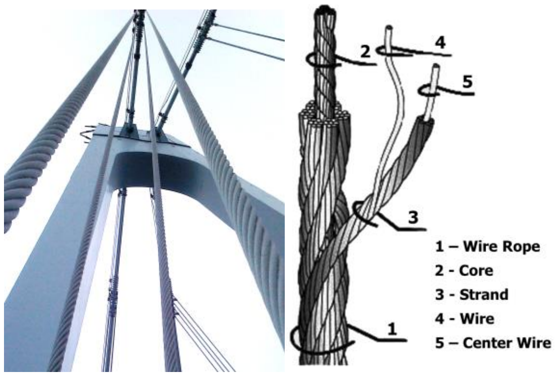
Previously, we have developed a climbing robot targeting the inside and outside inspection of hanger cables [8]-[10]. The robot called Multifunctional Robotic Crawler for Cable INspection (MRC^{2}IN-I) consists of three identical modules, and modules are placed 120 degrees apart circumferentially. Each module has a driving unit and an adhesion unit, and the driving unit is composed of a driving mechanism and a safe-landing mechanism. The functional performances of the robot mechanisms about an adhesion mechanism, a driving mechanism, and a safe-landing mechanism were verified under the indoor experimental environment composed of a wire rope of diameter of 76.2mm. MRC2IN-I showed reasonable transportation capability but it was observed that the robot was being oscillated while driving on the hanger cable owing to the twisted surface of the hanger cable. It may be the result in the abrasion of the tire and the breakaway of the robot. As an advanced mechanism, the caterpillar mechanism was equipped to MRC2IN-I+ in place of the wheel and the driving stability of the robot was considerably improved [11], [12].

In this paper, we introduce a totally redesigned robot, called MRC2IN-II which solves the most of problems in the previous robots. The operating principles of the mechanisms are explained and the results of indoor/outdoor experiments are given.

The paper is organized as follows. In the first, the requirements of a climbing robot for the inspection of the hanger cable are addressed in Section II. Section III introduces the mechanisms of newly developed MRC^{2}IN-II. The performances of the robot are verified experimentally by Section IV. Finally, conclusions are given in Section V with the future works.

II. REQUIREMENTS OF CLIMBING ROBOT FOR INSPECTION OF HANGER CABLES

The diameter and length of hanger cables are different depending on the scale of the suspension bridge. For example, the ultra large span suspension bridge used to connect between the land and the island, especially Young-Jong Bridge in Republic of Korea as shown in Fig.1 (a), the diameter and length of the cable are up to 84mm and 200m, respectively. By targeting the cables of the medium-to-large suspension bridges, we have specified the goal range of cables with the diameter of the cable of 40~85mm, and its length of less than 200m. The human is hard to access to the cables in our goal ranges, and thus, the climbing robot can be an alternative for the human worker.



(a) (b)

Figure 1. (a) The hanger cables of Young-Jong suspension bridge, Incheon, Republic of Korea (b) The structure of the hanger cable [13]

If moving the robot from a cable to another cable takes long time, the total inspection time of a suspension bridge might be quite a long since a suspension bridge is composed of a lot of the cables. Therefore, the installation and removal process of the robot should be easy and simple. The hanger cable has the shape that are twisted strands with a core as the center as shown in Fig. 1 (b). The strand is made up with twisted wires. The twisted shape is like uniform terrains appearing periodically in the side of the robot. Namely, the robot should overcome the bumpy surface of the hanger cable. Since this issue was solved in previous work by using the caterpillar mechanism [11], [12], a caterpillar-based climbing robot is suitable for cable climbing. Furthermore, the diameter of the hanger cable is not actually identical in every section because the twisting of the hanger cable is able to be loosened. It means that the robot should be able to cope with a little change of the diameter. Above all, the robot should be able to transport the inspection device such as cameras and NDT because the ultimate goal of the robot is the inspection of the inside and outside of the hanger cable.

Based on the conditions mentioned above, the requirements for a hanger cable inspection robot are summarized as shown in Table. 1.

TABLE I. REQUIREMENTS FOR HANGER CABLE INSPECTION ROBOT

Applicable cable diameters	40 ~ 85mm
Inspection distance	~ 200m
Climbing speed	~ 0.08m/s
Applicable payload	~ 24Kg
Ability to cope with the diameter change	~ 10% of the diameter
Capacity to ensure safety	With safe-landing device
Installation time	~ 10 min
Driving type	Caterpillar based

III. MECHANISM DETAILS OF MRC^{2}IN-II

Considering the requirements of Table I, the multifunctional robotic crawler (MRC^{2}IN-II) is newly designed as shown in Fig. 2. MRC^{2}IN-II consists of an adhesion mechanism, two traction modules, and two sub modules. The traction and sub modules are faced each other, respectively. The specifications of MRC^{2}IN-II are listed in Table II.

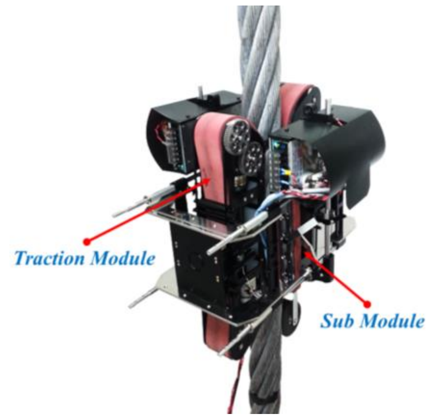


Figure 2. Multifunctional Robotic Crawler for Cable INspection - II (MRC^{2}IN-II)

TABLE II. SPECIFICATIONS OF MRC^{2}IN

Dimension	328.5 x 507.5 x 701mm
Mass	25Kg
Applicable cable diameters	40 ~ 90mm
Inspection distance	39.6m under indoor environment
Climbing speed	0.08m/s without a payload 0.05m/s with 24Kg
Applicable payload	24Kg
Ability to cope with the diameter change	13% of the diameter
Capacity to ensure safety	Safe-landing mechanism
Installation time	5 min
Driving type	Caterpillar based

A. Adhesion Mechanism

The adhesion mechanism generates adhesion force by using a screw-nut set and springs as illustrated in Fig. 3.

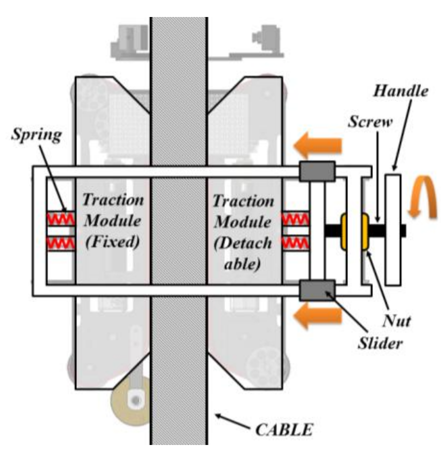


Figure 3. Operational principle of adhesion mechanism

The installation process of the robot is as follow.

- After placing the fixed traction module on the cable, assemble the detachable traction module, the nuts, and the adhesion mechanism with the fixed traction module along with the guides of the fixed traction module as displayed in Fig. 4.
- Rotate the handle of the adhesion mechanism in order to generate the adhesion force by compressing the springs after bolting the adhesion mechanism with guides of the fixed traction module (Fig. 5 (Left)).
- Tighten the nuts on the guides of the fixed traction module so as to fasten the detachable traction module. After then, disassemble the adhesion mechanism (Fig. 5 (Right)).
- Place the sub modules to the center of the hanger cable. Make the sub modules reach the hanger cable (Fig. 6). Fasten the clamps to keep the position of the sub modules.

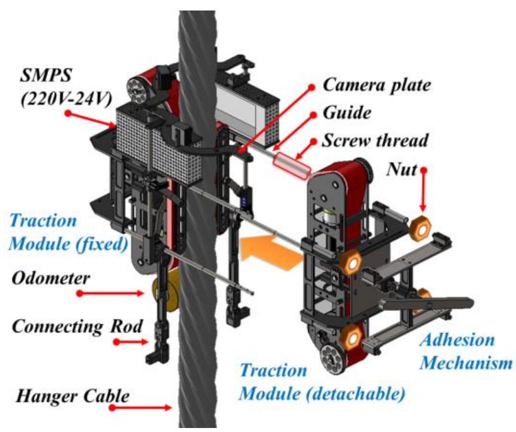


Figure 4. Installation process of MRC^{2}IN-II - 1

The simple and easy installation is able to reduce the installation and removal time. In addition, the weight of the robot could be decreased since the adhesion mechanism is designed to be detached after generating the adhesion force.

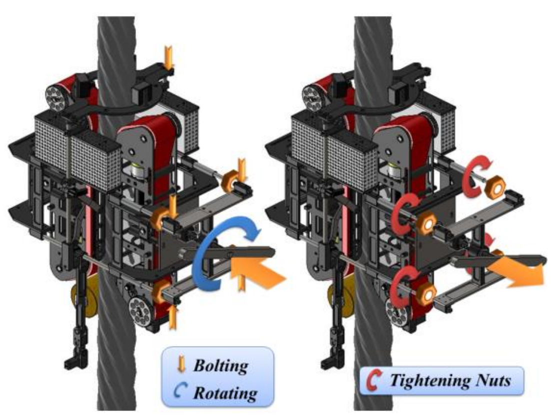


Figure 5. Installation process of MRC^{2}IN-II - 2

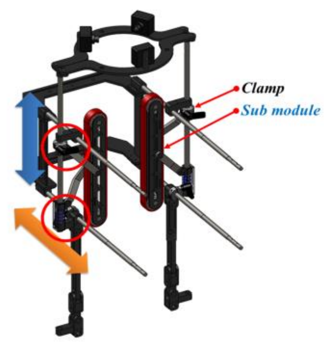


Figure 6. Installation process of MRC^{2}IN-II - 3

B. Traction Module

The traction module of MRC2IN-II has a shape of a caterpillar equipped with an odometer. The driving mechanism and safe-landing mechanism exist inside the traction module as shown in Fig. 7. The spur and bevel gear sets deliver the driving torque of the BLDC motor to the pulley, and the pulley makes the driving force by rotating the specially designed timing belt which is thermo-welded with rubber. The belt contacts with Ultra High Molecular Weight Polyethylene sheet (UHMW PE sheet) which is commonly used for a treadmill.

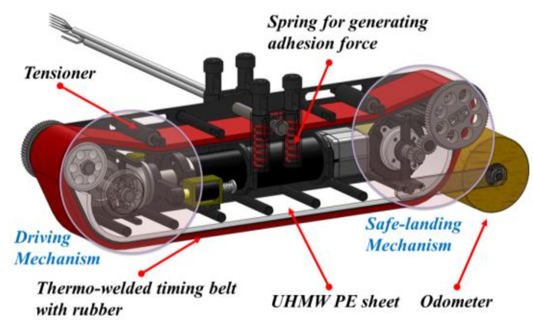


Figure 7. Traction module of MRC^{2}IN-II

In the emergency situation such as the failure of power supply, the robot may be stuck on the cable or fall down by gravity. In order to ensure the safety of the robot and an operator, the robot needs to have a safe-landing mechanism automatically activated when the emergency situation happens.

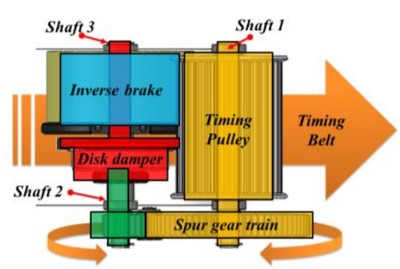


Figure 8. Operational principle of the safe-landing mechanism

The operational principle of the safe-landing mechanism is detailed as follows (Fig. 8).

- The timing belt is rotated by the robot weight, and the belt rotates the timing pulley.
- The torque of the pulley is transferred to Shaft 2 through the spur gear train.
- Since the inverse brake holds Shaft 3 when the power is not supplied and Shaft 3 is fixed with the body of the disk damper, the body of the disk damper could not be rotated.
- Shaft 2 rotates the inner part of the disk damper. The inner part is composed of silicon oil, and the applied torque is converted to the constant velocity depending on the viscosity of the silicon oil.
- Consequently, the potential energy of the robot is dissipated by the damper, and the robot is able to land safely.

On the other hand, the robot may be jammed at the stopped position by the very high-ratio gear train of BLDC motor combination when the power supply is lost. Thus, the driving mechanism has a clutch to prevent the jam. The clutch consists of the push typed solenoid, the spring, and the bar as shown in Fig. 9. The active bevel gear on the motor shaft is able to slide along the shaft of the motor. In case of supplying the power, the active bevel gear is combined with other bevel gears because the solenoids push the bar connected with the active bevel gear. Once the robot loses the power supply, the solenoids are returned to the original position, and the active bevel gear is released from the bevel gear train by the spring on the motor shaft.

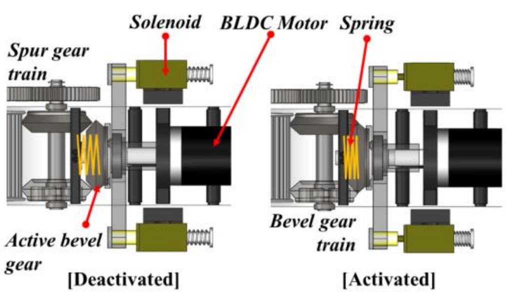


Figure 9. Solenoid-Spring based Clutch

C. Mechanism of Sub Module

The sub module has two passive pulleys, the thermo-welded timing belt with rubber, and Ultra High Molecular Weigh Polyethylene sheet (UHMW PE sheet, same as the components of the traction module (Fig. 10)). The sub module is able to be moved in the up-down and left-right directions because it is connected with the vertical and horizontal guides. In other words, the robot is applicable to various diameters of the hanger cables by adjusting the position of the sub modules. The springs on guides are passively compressed when the sub modules meet an obstacle. The robot is able to overcome the obstacle through the instant displacement occurred by the compressed springs. In addition, the position of the sub module can be simply and easily fixed by tightening the lever of the clamps connected with the sliders.

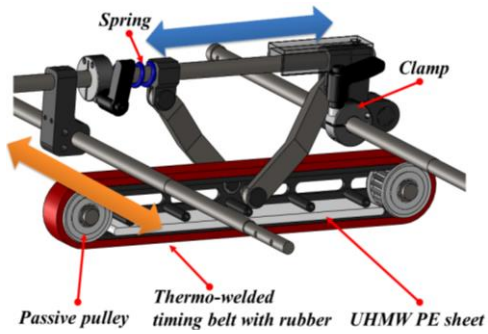


Figure 10. Sub module of MRC^{2}IN-II

IV. EXPERIMENTS

In order to verify the performance of MRC^{2}IN, the indoor and outdoor experiments were conducted. The experimental environment for the indoor experiments was organized with a wire rope of diameter 76.2mm and length 2m. The capabilities on climbing and safe-landing were evaluated under indoor experiments.

A. Climbing Capability

The robot was able to climb with 0.08 m/s without a payload. For the long-distance climbing test, the robot repeated climbing up and down 33 times at 0.05m/s in a 0.6m section of the wire rope without a payload. The total climbing distance was 39.6m and the error was 0.3m as shown in Fig. 11.

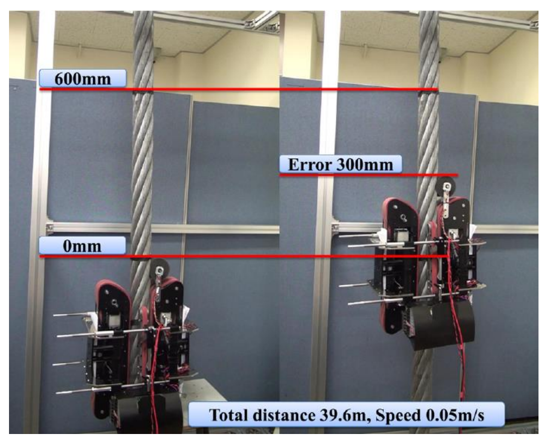


Figure 11. Long-distance climbing capability: (a) Initial position (b) Final position

Even though the caterpillar is good at the rough terrain drive and the adhesion force is exceedingly big, there must be a lot of slippage because the wire rope is vertically installed and it has bumpy surface. Fig. 12 shows the positions of each traction module and an odometer. The amount of slippage between each traction module and the wire rope was about 0.6m. The position of the odometer was exactly same with user command since the robot is controlled on the basis of an odometer. However, the odometer also slipped a little because real error was 0.3m.

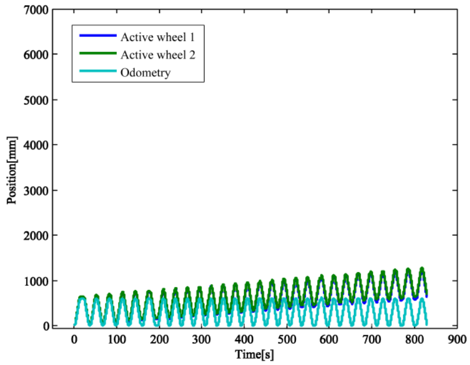


Figure 12. Position values of the long-distance climbing test

To verify a payload of the robot, a mass of 12 Kg was loaded on each traction module (Total 24 Kg). The robot successfully climbed a wire rope at 0.05m/s as shown in Fig. 13.

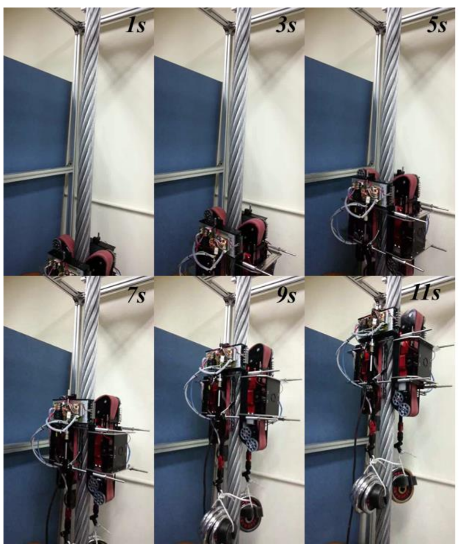


Figure 13. Verification of a payload of the robot

An obstacle of the diameter 86mm (about 13% larger than the wire rope diameter, obstacle of height 4.953mm for each traction module) was attached on the wire rope so as to test the ability to overcome an obstacle. The robot smoothly climbed over an obstacle at 0.05m/s by using the instant compression of springs as shown in Fig. 14.

B. Safe-landing Mechanism

To check the normal operation of the safe-lading mechanism, the power supply was suspended when the robot reached to end of the wire rope. The loaded payload was 24Kg. After the power interruption, the bevel gear train was released and the inverse brake held the shaft fixed with the disk damper body. In other words, the safe-landing mechanism was automatically activated as soon as the robot lost the power supply. The robot safely climbed down with similar descending speed as shown in Fig. 15.

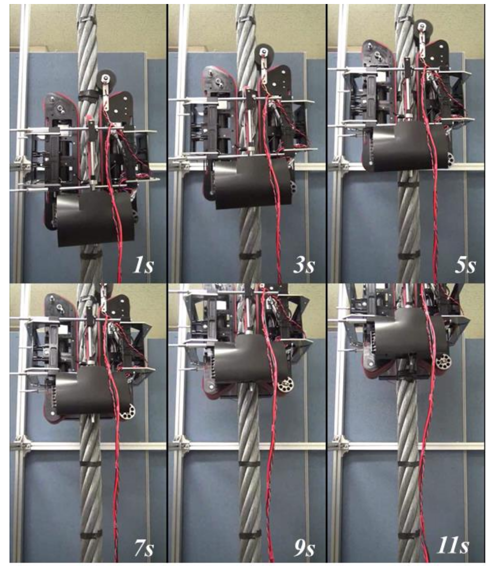


Figure 14. Test of ability to overcome an obstacle

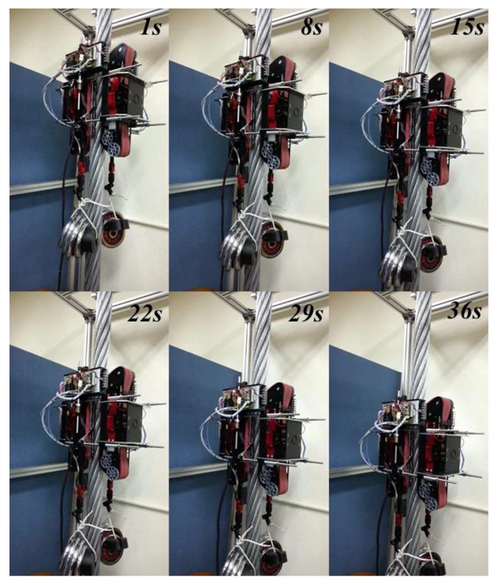


Figure 15. Test of ability to overcome an obstacle

C. Outdoor Experiment

For the verification of the robot performance under outdoor condition, the robot climbed on the small-scaled real bridge (Diameter: 79mm, Length: about 3m, Na-rae Bridge, Republic of Korea).

In this experiment, the robot was wirelessly controlled via Xbee^{TM} modules and the captured video data was also transmitted in real-time without a wire as shown in Fig. 16. Only electric power from portable gasoline power generator was supplied through the power cable.

The robot successfully climbed at 0.05m/s without a payload and the safe-landing mechanism was operated normally. The cable could be inspected with captured video data in real-time as shown Fig. 17.

Figure 16. Outdoor experiment setup

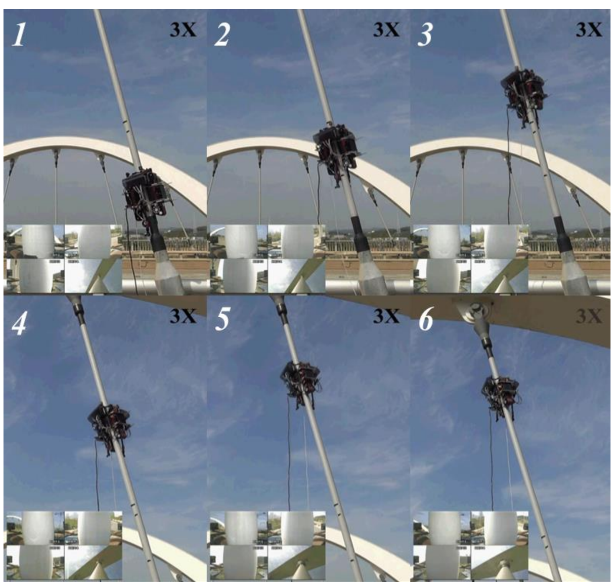


Figure 17. Outdoor experimental result

V. Conclusions

In this research, MRC^{2}IN-II that is the second model of Multifunctional Robotic Crawler for Cable Inspection robot series was introduced. It is newly designed one by improving the stability on moving and payload. The working principles of the robot were explained in details, and its performances were verified under indoor and outdoor environmental experiments.

As the future work, we are planning to combine MRC^{2}IN-II with NDT device such as Magnetic Flux Leakage sensor. In addition, the robot system will experience field tests in real long span cable suspension bridges.

Acknowledgment

This work is a part of a research project supported by Korea Ministry of Land, Transportation Maritime Affairs (MLTM) through Core Research Project4 of Super Long Span Bridge R&D Center (08 CTIP-E01).

Also, this research was partially supported by the Industrial Strategic technology development program, project number: (10033888, development of Anthropomorphic Robot Hand Technology for Delicate Dynamic Grasp) funded By the Ministry of Trade, Industry & Energy (MI, Korea).

The authors wish to express their gratitude for the financial supports.

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