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Development of Tele-Inspection Devices “MastCam” and “S2 Rover”

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Abstract

Nippon Steel & Sumitomo Metal Corporation is developing remotely controlled inspection devices for steel making plant. These kinds of robots may benefit us scaffold-free-inspection or inspection while factory runs. Our “MastCam” is the most functional hand-held pole camera system and a combination of off-the-shelf components and less-wire technology. “S2 Rover” is a self propelled inspection cart with magnetism wheels. They are made by rubber tire and a ring-shape magnet. The chassis has multi-joint and can fold it via torque control of each wheel; hence, this cart can run over the internal and external corner.

1. Introduction

The production facilities of the steelworks of Nippon Steel & Sumitomo Metal Corporation have been in operation for many years, and from a long-term viewpoint, many of them have to be replaced with new ones. It is difficult, however, to decide when and how to renew each of them and how to prolong the period of their safe operation is an important task for the company as a commercial enterprise.

Let us consider, as an example, an underground pipeline tens of kilometers long and operating for decades. Principally, there are the following three alternative philosophies for its renewal:

(1) Replacing the entire pipeline stopping and changing it all at once within a certain period: this involves a large investment in a short period and an operation stop.

(2) Constructing another one at a separate location while the existing one is usable and then switching to the new one: it is possible to avoid operation stop, but a separate land area and other resources are required.

(3) Dividing the line into several sections and replacing the sections one by one rapidly in the order of the risk of failure to complete the whole renewal within a prescribed period: operation stop is shorter and heavy investment is avoided, but this requires technologies for reliable judgement of failure risk and rapid replacement work.

The third alternative looks preferable at first sight, but the decision about the sequential order of renewal between the sections based on inspection and judgment on equipment degradation is not easy nor is their quick replacement. To overcome the difficulties, use of robots is considered helpful.

2. Characteristics of Inspection and Maintenance of Iron and Steelmaking Equipment

2.1 Structural characteristics of iron and steelmaking equipment

A steelworks is composed mainly of large and heavy plant facilities, many of which work under high loads and at high temperatures, and their very size and height make their inspection and repair troublesome. **Figure 1** shows an upstream process area of a steelworks including a blast furnace and related facilities. A blast furnace is ≥100 m high, and many related facilities are located at high positions.

There are hundreds of thousands of equipment points to inspect in a steelworks, and most of the “latest” steelworks in Japan have been in operation for more than 40 years; therefore, the maintenance costs are huge at any one of them. **Figure 2** compares some indus-

Fig. 1 Plants in ironworks including a blast furnace

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tries that are heavily equipped with infrastructure in terms of the percentage of maintenance costs to turnover. In many industrial sectors where heavy capital investment is required, maintenance and repair costs account for nearly 10% of the turnover, and efficient equipment maintenance is essential for business management.

2.2 Robotization of equipment inspection and maintenance

Maintenance activities consist of various phases: inspection to assess equipment conditions followed by planning, arrangement, and execution of repair work. Of these, inspection and repair work are done in direct contact with the object equipment, and there is much room for productivity increase by mechanization. The maintenance activities of the steel industry are structured as shown in **Fig. 3**. Since there are a great number of object facilities, many of which are hard to access as stated earlier, mechanizing and robotizing their inspection, repair, and other on-site work are desirable. Robots are effective because they are capable of inspecting and monitoring conditions of hard-to-access equipment at high or cramped places or high temperature.

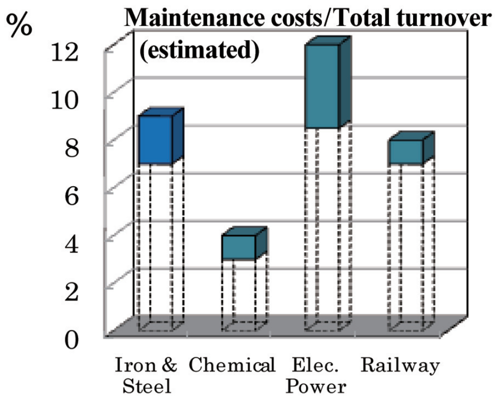


Fig. 2 Ratio of maintenance cost in different fields of industry

3. Characteristics of Robots for Equipment Inspection and Maintenance

A big advantage of the use of robots for the inspection and maintenance of steel-producing equipment is their ability to work at high or cramped places where people can work only precariously. Their use is good for working safety, enhancing work accuracy, and reducing costs markedly because it enables inspection and repair while the object equipment is running. It has to be noted, however, that presently autonomous locomotion of robots is not economically recommendable, and for the time being, inspection and maintenance robots will be mainly of a remotely controlled type.

Many iron- and steel-producing facilities consist of steel structures, and unlike large concrete structures such as bridges and buildings, their inspection is conducted in direct contact or at a distance of 1 m or less, but inspection robots presently available do not always have the ability to come close to object equipment. When robotization is discussed, photographing is often considered as the principal manner of equipment inspection, but it is desirable to also robotize the inspection work that has to be done in direct contact such as thickness measurement. **Figure 4** compares the closest approach to objects and the tele-operating distances of presently viable carriers of inspection sensors, namely, pole cameras, magnetic

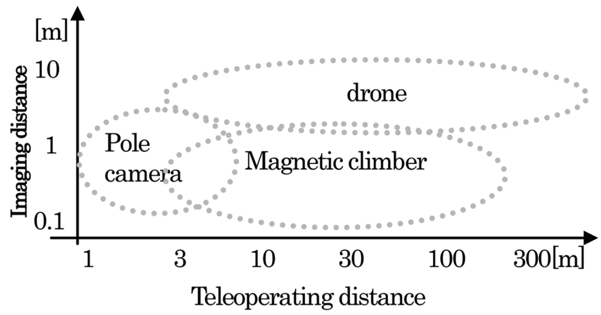


Fig. 4 Maintenance robot and teleoperation distance

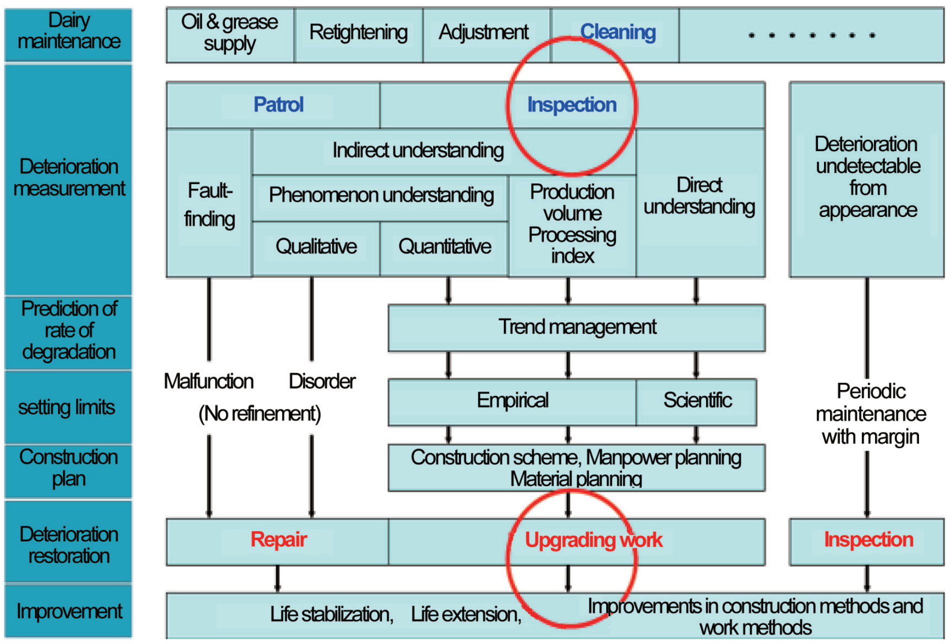


Fig. 3 Maintenance process and robotization

climbers, and drones (small multirotor aerial vehicles, etc.).

The graph shows that drones and other unmanned aerial vehicles are, although excellent in mobility, still very limited in access to object equipment. At present, pole cameras and magnetic climbers are more suitable, but their applicability is also limited.

4. Pole-Camera-Type Inspection Robots

4.1 Application examples and problems of multipurpose pole cameras

Industrial endoscopes are widely used for equipment inspection; for large machines, they are used in variations such as a long pole with a camera or a site window of fiber optics at the probing end; **Figs. 5** and **6** show such examples.[1, 2] The portable gooseneck camera shown in Fig. 5 is 3 m long when extended and is usable manually in a vertical or horizontal position, but in exchange for its light weight and simple structure, the direction of sight has to be set beforehand. Another model can be extended to roughly 10 m; its use position is limited to vertical only, but the direction and width (zooming) of view are remotely changeable. The price of the shorter model is about ¥100 000 per set, and the longer one about ¥500 000 (approximately ¥110/US$).

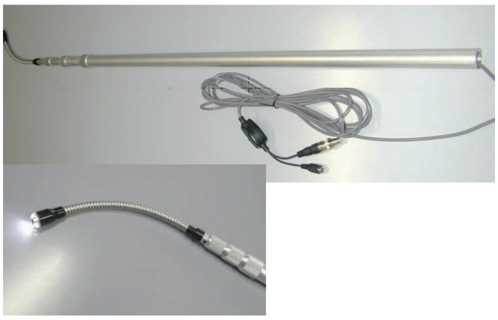


Fig. 5 Goose-neck camera[1] (FJ-EX310L/610L by Kuroda Optonics Corp.)

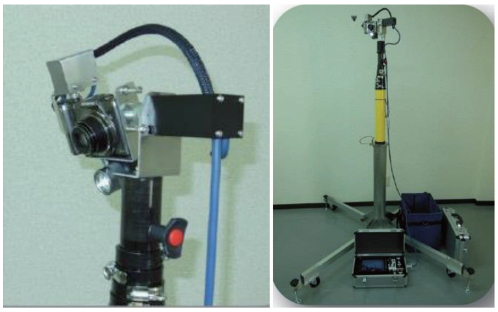


Fig. 6 Pole camera[2] (PCS1201 by Intes Corp.)

For practical use for the inspection of iron- and steel-producing equipment, the pole cameras must have the following features:

(1) It can be handled manually by one person in desired attitudes,
(2) The direction and zooming of view are remotely changeable, and
(3) The person holding the camera can monitor the view during recording.

Since there were no models of pole camera satisfying the above conditions in the market, Nippon Steel & Sumitomo Metal decided to develop one according to the target specifications given in **Table 1**.

4.2 Configuration and functions of the developed pole camera

Figure 7 shows the developed pole camera, which was named MastCam, and **Table 2** shows its main specifications. In addition, **Fig. 8** shows the movement of its viewing head. The pole, about 1.5 m in length, can be extended to a desired length up to 5.2 m by turn of a lever. A beam, slightly less than 1 m in length, is provided at the top end of the flexion type; it can rotate in 180° and flex in L-shape. The image being recorded by the camera can be seen real time on a monitor provided at the operator end, and the optical axis of the camera can be turned and tilted as desired by small servo motors in the mount and operated from a control box provided near the hand hold. Zooming of the view, shooting of still photos (high resolution

Table 1 Target specification of pole camera

	Goose-neck camera (Kuroda Optonics)	Pole camera (Intes)	Target spec.
Holding method	Hand held	Base holding	Hand held
Resolution	SD (VGA)	HD (Full HD)	HD (Full HD)
Camera pan & tilt	Preset	Tele-operation	Tele-operation
Extension length (m)	3.2	11	5
Contraction length (m)	0.5	1.2	1.5
Weight (kg)	2.0	6.0	3–4
Price (M¥)	0.1	0.5	1.5 (cost)

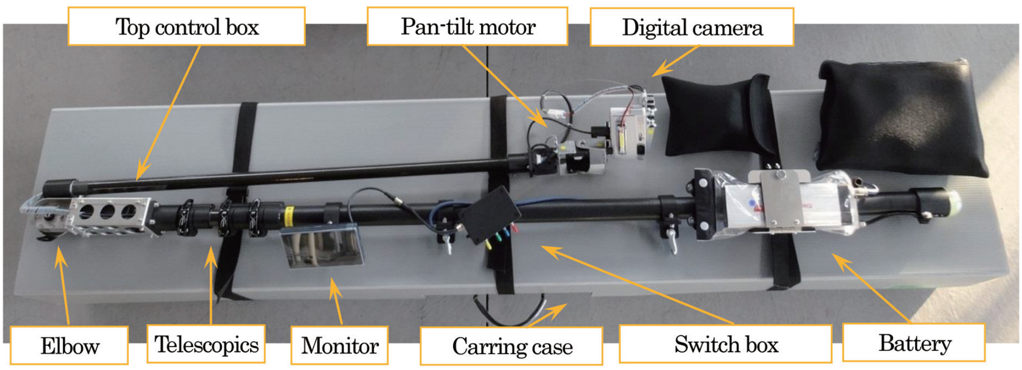


Fig. 7 MastCam (flexion type Version 2.0)

Table 2 Variation and specification of MastCam

Specification	Short type	Flexion type
Basic specification	Tip camera: Full HD compact (10× zoom) Imaging function: Still (18Mpix) / Motion (FHD) Pole end monitor: 4 inch LCD (VGA resolution) Operation: Pole end switches (camera control, flexion, and rotation), preset telescope and elbow Tip lighting: LED (3W) Pole: Telescopic CFPR poles Power supply: Pole end battery (rechargeable) Environmental: 0–50°C, drip-proof (IP5x)	
Extension and contraction length	4 m/1.5 m	5.2 m/1.6 m
Tip flexion and rotation	1 preset rotation + 1 flexion (motorized)	2 preset rotation & flexion + 2 rotation & flexion (motorized)
Weight	3 kg	3.5 kg
Accessory	Battery recharger, straps & fall-prevention hook	
Price (M¥)	Around 1.2	Around 1.5

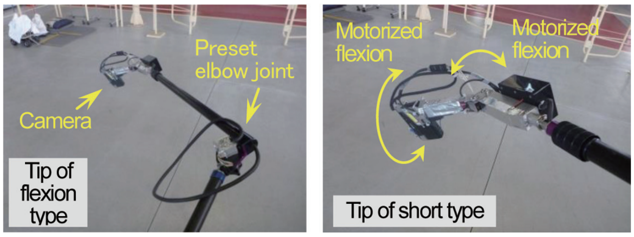


Fig. 8 Camera orientation controller and its motion

up to 18 M pixels), and LED lighting can be operated from a switch board at the operator end independently from video recording; flash light is provided for shooting still pictures.

For weight and cost reduction, the camera is a common compact digital camera available in the market and fitted to the remote-controlled tilting mount, which is driven by small servo motors available at hobby stores. The signal is transmitted by the serial link via a cable running inside the telescopic tube for one-person operation. Thanks to the optimum combination of commonly available components and simplified cabling, the developed pole camera has high and widely varied functions unprecedented among existing hand-held pole cameras.

4.3 Adequate extension length of pole camera

When fully extended to 5.2 m, the center of gravity of the flexion type MastCam falls at about 2.1 m from the holding end. Supposing that it is held horizontally at a position 0.7 m from the end, the twisting moment at the holding positon exceeds 100 N, which indicates that the maximum length of 5.2 m is near the limit for practical use.

4.4 Actual application

Figure 9 shows a scene of the field use of MastCam; actually, the object, a continuous annealing and processing line (CAPL), was stopped at this time, but it was inspected without requiring some of otherwise obligatory safety and preparatory measures, which proved the usefulness of the developed pole camera for urgent need. Presently, it is used effectively at the plant maintenance and operating organizations of several steelworks of the company. The possibility

Fig. 9 Inspection scene and picture of crack in insulation plate taken with pole camera (Apr. 2015)

of expanded use of the device for normal production activities (monitoring of operation parameters, product quality, etc.) is now being studied.

5. Inspection Robots with Magnetic Attraction Wheels

5.1 General-purpose robots—Precedent development studies and technical problems

Various types of devices that can access high places via vertical walls making use of magnetic attraction have been developed and actually used for inspecting steel structures, but their commercial use has not been established because sometimes it is difficult to maintain the attraction, and the ability of access is limited or lost.

(1) Existing models

Various nondestructive inspection companies have developed and used different types of self-propelled equipment inspection cars using magnetic attraction. **Figure 10** shows one such example of Shin-Nippon Nondestructive Inspection Co., Ltd. The vehicle runs on planetary wheels and is capable of surmounting steps up to 75 mm in height, which is nearly equal to the effective radius of a set of the planetary wheels.

(2) Structures proposed in patent applications

Real steel structures have many protrusions and depressions due to ribs, joints, etc., and for a vehicle to reach a position to inspect, it must have the ability to cope with such irregularities. As a mechanism to negotiate those irregularities, Japanese Unexamined Patent Application No. H9-142347 (uneven terrain mobile device[3]) by Mitsubishi Heavy Industries, Ltd. proposes a wheel suspension structure using manipulators (see **Fig. 11**). Since this structure requires strong manipulators, which means heavy weight and high price, there have been few applications.

Taking advantage of the fact that a magnet wheel maintains adhesion even at a corner of a steel object, Japanese Unexamined Patent Application No. S62-26172 (magnetic attraction vehicle[4]) by Babcock-Hitachi K.K. proposes a single-axle, two-wheel vehicle that can surmount corners; **Fig. 12** shows a typical example of such a vehicle. By this configuration, at least one auxiliary wheel is required to obtain reaction force for locomotion. The problem is that when it surmounts a protrusion, it may lose balance and the magnetic attraction as well, which is likely to happen with a two-wheel vehicle.

(3) Example outside Japan

The École Polytechnique Fédérale de Lausanne, Switzerland, actually constructed some units according to the idea of the said

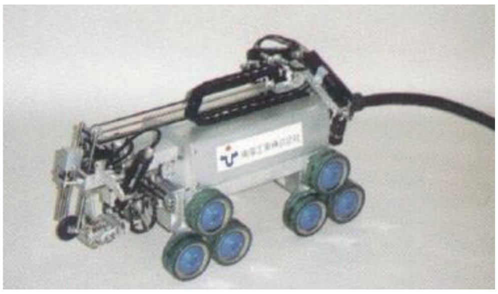


Fig. 10 Chimney wall thickness measurement robot (planetary wheel type, joint development of Shin-Nippon Nondestructive Inspection Co.,Ltd. and Toden Engineering Co.,Ltd.)

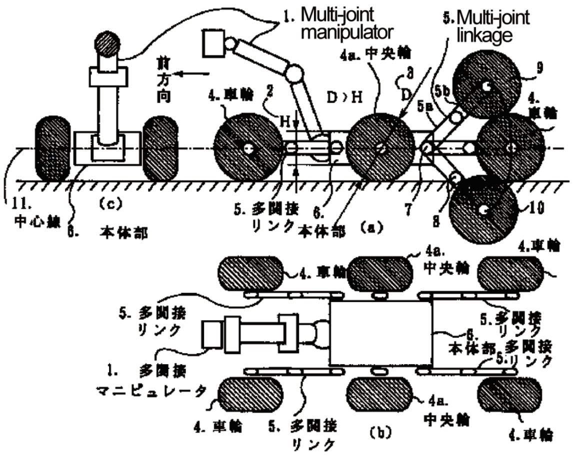


Fig. 11 Uneven terrain mobile devices[3]: J. U. P. A. P. No. 2007-142347 by Mitsubishi Heavy Industries, Ltd.

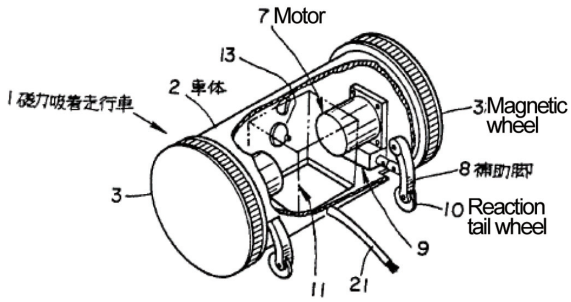


Fig. 12 Magnetic attraction vehicle[4]: J. U. P. A. P. No. S62-26172 by Babcock-Hitachi K.K.

two-wheel vehicle, and actually realized the effects envisaged in the patent application.[5] Those units, however, could not carry a payload of a certain size and weight for equipment inspection such as a high-resolution camera, and probably for this reason, were not brought to practical use (see **Fig. 13**).

5.2 Development target

For the development of a self-propelled equipment inspection car with magnetic attraction wheels, Nippon Steel & Sumitomo Metal set forth the following three points as the features to realize:

(1) The capacity to surmount steps approximately 30 mm in height (roughly equal to the radius of the wheels);
(2) A structure that can negotiate protrusions and depressions in the path; and
(3) A loading capacity for 2 kg, approximately.

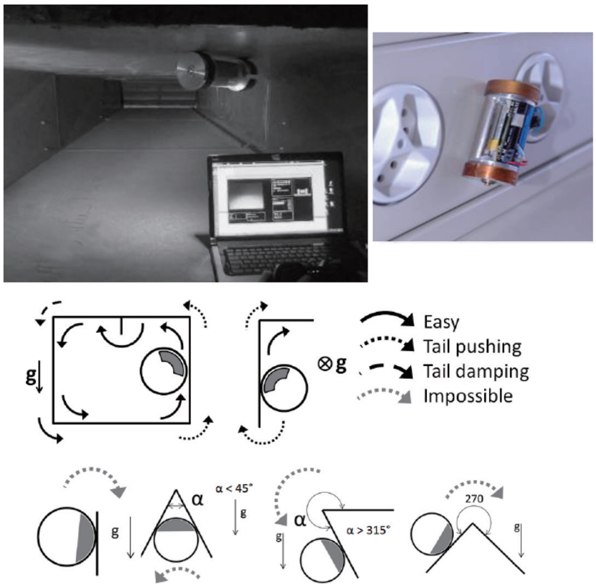


Fig. 13 CyMag3D École Polytechnique Fédérale de Lausanne (EPFL)[5]

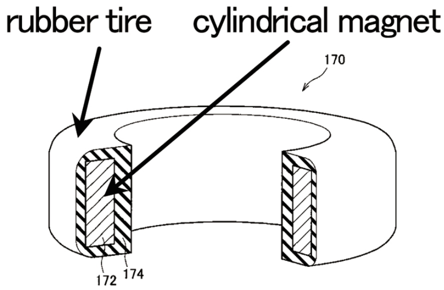


Fig. 14 Magnetic wheel structure of S2 Rover

5.3 Construction and functions of developed vehicle

The new equipment inspection car, which was named S2 Rover, was developed as described below.

(1) Development of magnet wheels

A cylindrical magnet of neodymium is wrapped with a rubber tire and the tire/magnet unit is fitted onto a plastic wheel center; the diameter of the wheel is 90 mm and the width 35 mm, approximately (see **Fig. 14**). To cut costs, soft rubber tires for radio-controlled model cars available at hobby stores, etc., having a tread pattern for off-road use suitable for securing good adhesion on rough surfaces, were selected. A high friction coefficient is of vital importance for locomotion on vertical surfaces, and for this end, rubber tires as soft as possible were looked for in the market.

(2) Vehicle configuration

S2 Rover is an articulated, electric-motor-driven, three-axle, and six-wheel vehicle 420 mm in length, 190 mm in width, and 4 to 5 kg in weight. The articulation joints are parallel to the wheel axles, and each of the six magnet wheels explained above are driven independently. Two types are available: the flat type having one articulation joint and the flexion type having four joints, the latter being capable of traveling over ribs and similar obstacles (see **Fig. 15**); **Table 3** compares the specifications of the two. The two wheel axles at the ends are steerable and the one at the center is fixed. Since all the wheels are driven independently, the driving force of the two wheels of each axle can be differentiated to facilitate steering.

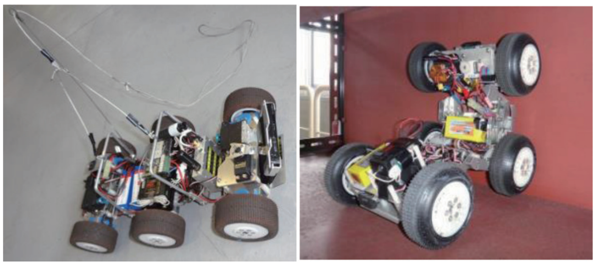


Fig. 15 S2 Rover (left: flat type, right: flexion type)

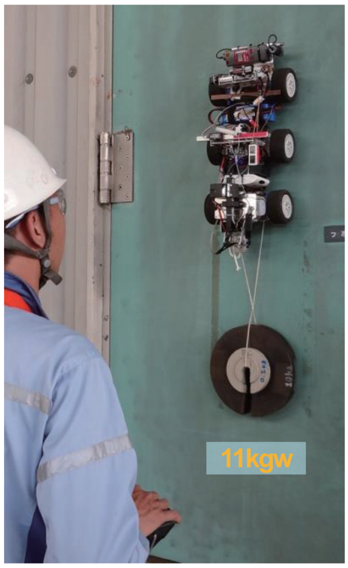


Fig. 16 Payload capacity test of S2 Rover

Table 3 Variation and specification of S2 Rover

Specification	Flat type	Flexion type
Basic specification	Wheel: Rubber tire + Magnet ring (rare earth mag.) Tele-operation: Steering/forward & backward, radio Power supply: On-board battery (rechargeable) Environmental: 0–100°C, Battery life: 1–2 h approx.	
Inspection function	Tip camera: HDV compact Imaging function: Still (18Mpix) / Motion (FHD) (10× zoom) Operating monitor: VGA Lighting: LED 3W	- (Loading equipment under consideration)
Characteristic	Flat surface, high load	Pass over corners
Weight	4–5.5 kg	4.0 g
Payload	3–10 kg (up to friction situation)	1 kg approx.
Standard accessory	Radio transmitter, recharger, operating monitor, fall-preventive wire	
Cost (M¥)	4.5 approx.	4 approx. (vehicle only)

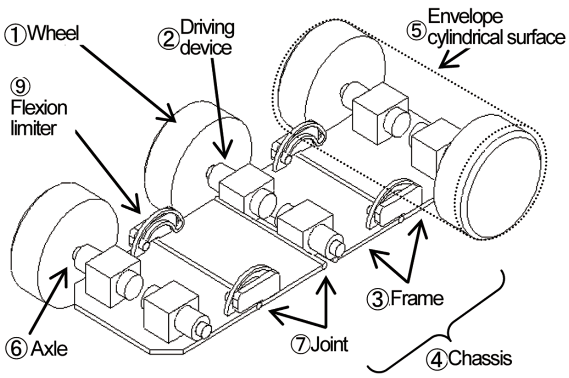


Fig. 17 Flexion body structure of S2 Rover

(3) Evaluation of loading capacity

The loading capacity of S2 Rover was tested using a flat-type unit; **Fig. 16** shows a test scene. Since the loading capacity on a vertical surface is governed by the friction coefficient, it changes depending on the condition of the surface. Through a series of laboratory tests, S2 Rover proved capable of hauling a maximum load of roughly 11 kg on a vertical door of painted steel plate, and another of about 5 kg on a ceiling surface (facing downward). When loaded close to the above limits, the wheels slipped considerably and the vehicle moved with difficulty. Nevertheless, since the flat type cleared the target loading capacity of 2 kg at the test, it was regarded to be capable of carrying a camera or other inspection facility. The possibility of loading S2 Rover with a contact-type inspection device such as an ultrasonic thickness gauge is now being studied.

With the flexion type, the room for a camera or some other inspection device is rather limited because of the large movement of the articulation joints, and development studies on device mounting continue.

(4) Flexion body frame

The flexion type S2 Rover has been developed as a vehicle capable of surmounting ribs and other protrusions, and as such, it has an articulated structure as illustrated in **Fig. 17**. (For simplicity's sake, only three articulation joints are shown, and the steering mechanisms are omitted.) The flexion of the joints are limited to stabilize the vehicle movement at protrusions and recesses. **Figure 18** illustrates how the joints move under different situations, and **Fig. 19** shows how the vehicle negotiates an edge of a steel plate. Rib edge surmounting performance has been tested with ribs protruding upwards, horizontally, and downwards, and they were overcome with substantially the same ease, but there remains a probability of failure of a little below 1%, and improvement measures are being looked for. An important factor is the speed of approach to the obstacle.

Table 4 compares different articulation structures so far proposed. The method of S2 Rover, whereby the articulation joints are controlled by means of the driving force of the wheels, requires a small number of actuators and is practically effective.

5.4 Application examples

Figures 20 and **21** show a scene of actual use of S2 Rover for inspecting a wharf unloading crane for raw materials at one of the company's steelworks in June 2011, and a picture taken from the vehicle on the occasion. When the East Japan big earthquake occurred in March 2011, the carne was unloading ore from a bulk carrier when a cargo ship carried by the tsunami hit the horizontal cantilever beam of the crane extended over the bulk carrier, and the beam was lost. The inspection was conducted as part of the preparation for the restoration work of the beam. A flat-type unit of S2 Rover was used for verifying the soundness of the welded joints of the crane pedestals, and the pictures it took were used for judging if the pedestals would be good for the restoration work and the operation thereafter. The flat type is capable of negotiating protrusions up to

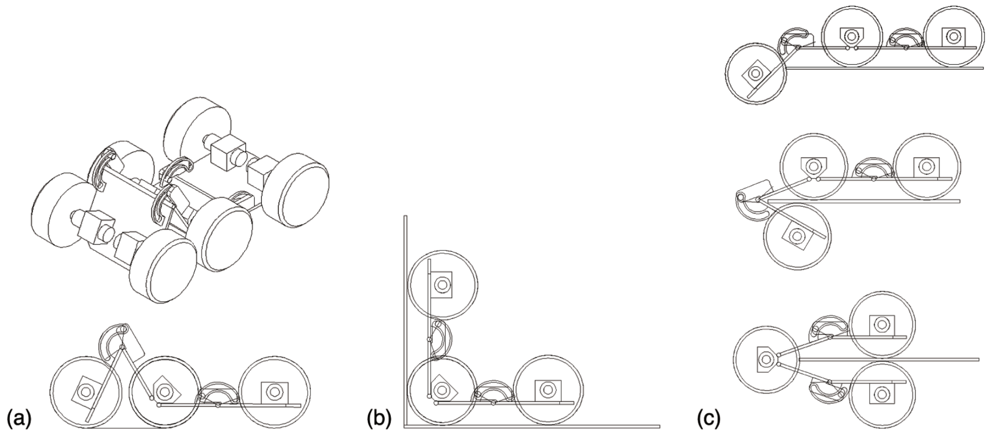


Fig. 18 Motion of flexion body joints (a) Limitation of joint angle, (b) Action over a concave corner, (c) Action over a convex corner

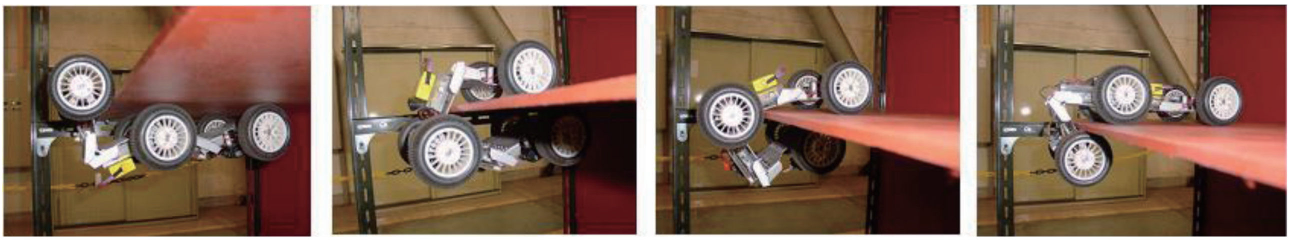
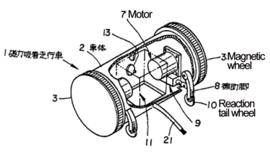
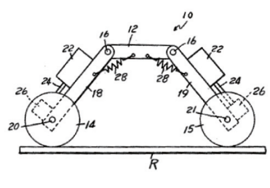
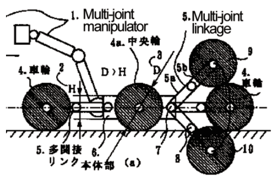
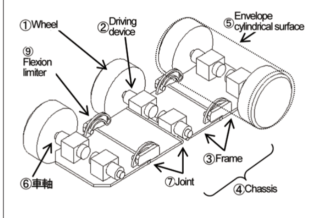


Fig. 19 Joint action over convave corner (from left to right)

Table 4 Comparison and characteristics of preceding researches and S2 Rover

	Two wheel and tail type	Jointed chassis type		
Structure	Reaction tail wheel	Passive joint	Controlled joint	Tension controlled
Applicant	Babcock-Hitachi (EPFL)	Individual (Kubota)	Mitubishi Heavy Indstries	Nippon Steel & Sumitomo Metal
Concept	Tail, i.e. legged wheel, takes reaction force (like toy bobbin car) 	Multi-jointed chassis, held by spring (J. U. P. A. P. No. S54-131209, magnet wheeled cart with all wheel drive) 	Multi-jointed chassis, controlled & held by actuator 	Multi-jointed chassis ・Free joint with flexion limiter ・Torque difference makes tension & repulsion, joint angle changes 
Advantages	Simple structure and light weight	Simple structure and low cost	Freely deformable chassis posture	Freely deformable chassis posture without joint actuator, light weight
Dis-advantages	Fluctuation of adhesion force → large fall risk	Lack of posture control, less adhesion control on vertical or uneven surface → large fall risk	Heavy joint actuators, complicated control law → expensive system	Control law for chassis tension & repulsion (may require to sense its posture)
Achievement	Test machine	Test machine (for model use only)	Concept	Test machine - some application
Overall rating	△	×	×	○

○ : Practical, × : Impractical, △ : Experimental

Fig. 20 S2 Rover climbing gantry crane stanchion for inspection (Jun. 27, 2011)

Fig. 21 Picture of crane stanchion taken by S2 Rover (Jun. 27, 2011)

30 mm or so in height, and its use for inspection of other works facilities is being studied.

6. Closing

The technical issues related to the remote-controlled equipment inspection devices, MastCam and S2 Rover, that Nippon Steel & Sumitomo Metal has developed and the studies during their development have been presented herein. They were developed to make up for the shortcomings of prior similar attempts, and as a result, vehicles adequately usable for condition inspection of iron and steelmaking facilities have been devised. On the other hand, it has become clear that further studies are required on related aspects such as function improvement, method of use, and specific kind of application; R&D resources are being input for these ends. These devices will be instrumental for improving the efficiency of equipment inspection of the steel industry by enabling the work where footholds are not provided or during normal operation.

Acknowledgement

The author would like to express his heartfelt gratitude to Mr. Akira Kamide, President, the members of the development team, and the people involved of Intes Corporation who manufactured the prototypes of the developed machines. The author also thanks Mr. Seishiro Nakazawa of Meitec Corporation for his help in the studies to define the orientation of the development.

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