Research article

Tele-operated climbing and mobile service robots for remote inspection and maintenance in nuclear industry

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Abstract

Purpose – Aims to report on the various types of tele-operated mobile service robots for remote inspection and maintenance, especially in the field of nuclear industry.

Design/methodology/approach – Describes nuclear electric robot operator (NERO), Sizewell A duct inspection equipment (SADIE), Robug-IIs (all leg-based) and Roboslave (wheel-based).

Findings – That these robots can handle a significant portion of inspection and maintenance tasks in a typical nuclear plant, though, given that they are primarily tailor-made, they are still too expensive for ordinary industries.

Originality/value – As the interests of health and safety and paramount, this study sees the use of such robots expanding and diversifying, irrespective of cost.

Keywords Remote handling devices, Robotics, Nuclear technology

Paper type General review

1. Introduction

Inspection and maintenance is essential in the nuclear industry. Failure in carrying out proper maintenance could increase the chance of accidents which could result in severe casualty not only inside the nuclear plant but also in the nearby community. However, it is not easy to carry out such maintenance tasks since the environments are usually highly radioactive, and unsafe for human workers to work in such locations. The usual way of carrying out the inspection and maintenance task in a hazardous environment is to use long-reach and fixed-base manipulators. However, the manipulator will suffer from low payload capacity and relatively large end point deflection. Also, the installation and the storage of these long manipulators can be costly. An alternative solution is to use the mobile service robot installed with appropriate tool package or manipulator, which can overcome the problems encountered by the long-reach manipulator.

Over the years, a number of service robots, especially the climbing ones, have been developed for various applications (Wang and Shao, 1999; Grieco *et al.*, 1998; Sato *et al.*, 1991; Bahr and Yin, 1994; Pack *et al.*, 1997; Nishi, 1996; Hirose *et al.*, 1991; Kroczynski and Wade, 1987; Briones *et al.*, 1994; Guo *et al.*, 1994; Tso *et al.*, 2000; 2001; Zhang *et al.*, 2001; Hillenbrand *et al.*, 2001; Sattar *et al.*, 2001). These robots are mainly engineering prototypes for the purpose of proof of concept. This paper will report the various types of tele-operated mobile service robots which are developed by the authors. They include nuclear electric robot operator (NERO) series, Sizewell A duct inspection equipment (SADIE) series, Robug IIs and Roboslave. These robots are designed for the remote inspection and maintenance tasks, especially applied to the field of nuclear industry.

NERO and SADIE are two series of walking and climbing service robots which have been applied successfully to inspect two Magnox reactors in the UK. In order to overcome the

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difficulty in launching these climbing service robots in confined environments, Robug-IIs, an articulated legged walking-and-climbing service robot, is developed. It is designed to work in a relatively unstructured and rough terrain. Practically, it is capable to walk on rough floor, climb up vertical surface, and perform autonomous floor to wall transfer. On the contrary, Roboslave is a general-purpose wheel-based mobile service robot applied to flat floor area. The distinct feature of Roboslave is being tele-operated by a pair of hand-held robot end-effector representatives (REERs) that helps to apply the robot to a nuclear plant for tasks such as handling radioactive substances, and turning off emergency valves inside a hazardous area. Human operator performs the task with the REERs in a safe control room while the remote robot follows the operator motion and executes the demonstrated task.

2. NERO series of climbing robots

Magnox type nuclear reactors form the early generation of commercial nuclear reactors in the UK. In order to extend the life of an early-built reactor, a non-destructive test (NDT) programme is set-up to inspect part of the reactor pressure vessel (RPV) at the Trawsfynydd nuclear power station. Since, the design of this reactor provides only limited access for engineering servicing, fixed-base manipulators with multiple linkages cannot reach all the required areas of the RPV. As a result, NEROs are designed to carry out various tasks of the NDT programme. NERO is a pneumatically driven non-articulated legged vehicle. It uses vacuum gripper feet to hold on the RPV surfaces. It is originally designed to assist the installation of additional thermocouples onto the RPV surface. However, for the later designs of NERO II and NERO III, they are, respectively , fitted with wire brush and metal cutter for the preparation of obstacle-free access and robot movement. For small obstacles, NERO is capable to step over them, and crawl under low overhangs.

2.1 Design constraints

NERO is designed to work on the outside surface of an RPV. The RPV is an 18.7 m diameter welded steel sphere structure. The vehicle has to cope with this curvature and with any local variations. A cooling hood is situated over the top of the vessel to direct a flow of cooling air over the crown of vessel (Figure 1). The gap between the cooling hood and the vessel is approximately 250 mm (Figure 2). This gap restricts the height of the mobile vehicle. There are a number of thermocouples installed on the surface which are up to 25 mm high and which the mobile vehicle is required to step over. Owing to the prohibited access to the RPV because of the radiation hazard, the vehicle has to be driven remotely by an operator at the end of a 100 m umbilical cable. Since, the RPV surface is potentially covered with contaminated substances, it is an important design constraint that the feet do not collect loose material in order to allow the operators to service the vehicle. The surface preparation tools are heavy and together with the weight of the umbilical power and communication cable, NERO has to be powerful.

2.2 Mechanical system

All the NERO type of tele-operated vehicles shares the same basic drive mechanism consisting of two rectangular structures – a frame and a shuttle. The frame is the outer moving structure and the shuttle is the inner moving structure. Each structure carries four specially designed vacuum gripper feet which are attached onto pneumatic "leg" cylinders. This arrangement allows the vehicle to step over 25 mm obstacles without the need of excessive headroom. In order to ensure that the vehicle can be operated on uneven and rough surfaces, redundancy has been built into the system. The whole robot can be held onto the surface with only two front feet or a diagonal pair gripping. Compliance is obtained by feedback control of the leg cylinder pressures and also by ball joints between the "leg" cylinders and the gripper feet.

The translation movement of the structures is achieved by a double acting pneumatic cylinder. The ends of the cylinder rods are attached to frame whilst the cylinder body is attached to a metal plate on the shuttle. This metal plate is connected to the shuttle rotary centre column. Rotary actuation is achieved by a further double acting cylinder which is mounted on the shuttle plate and linked to the shuttle rotary centre column. Both translation and rotation pneumatic cylinders are controlled by solenoid valves. A pulse width modulation method is used to drive the cylinders in a force and position servo control system. The choice of pneumatic actuation gives the vehicle the high power to weight ratio and inherent compliance which has been found essential for climbing vehicles.

Motion is achieved by sequences of stepping, sliding and rotating movements. In order to move the vehicle, one structure will stand with its feet gripping on the surface whilst the feet of the other structure will be lifted and free to move. This allows the structure with its feet lifted to rotate or translate. Movement in the same direction is achieved by swapping the raised structure with the gripping structure. An all 8 ft gripping stage is implemented between swapping gripping structure to ensure maximum safety while walking on the RPV surface.

In order to avoid picking up contaminated substances from the surface, the gripper foot develops its vacuum from a compress air ejector pump. By reversing the flow, the air ejector cleans the filter in the foot and at the same time clears loose material on the surface prior to gripping.

Safety is one of the important considerations in the design stage of NERO system. The pneumatic control valves are arranged so that in the event of electrical power failure, the system will be fail-safe by lowering the vehicle on to the surface so that it grips with all eight feet in its lowest profile mode. The pneumatic supply system uses two compressors and one automatic selection valve to protect the NERO system from pneumatic supply failure. Wherever possible a safety wire is taken up to avoid damaging force in the event of a fall.

Three NERO type vehicles have been built. NERO I carries a special tape feeder for installing additional thermocouples (Plate 1). NERO II has a rotating wire brush for removing loose materials from the RPV surface. NERO III (Plate 2) has a 1.3HP rotary disc grinder fitted on a swing arm and is mainly used for removing unwanted studs and welding splatter from the surface.

2.3 Operational experience

Owing to the limited access to the RPV, all the mobile vehicles have to enter the void containing the RPV from the four entrances at the base of the biological shield. Vehicles have to

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Figure 1 Reactor pressure vessel

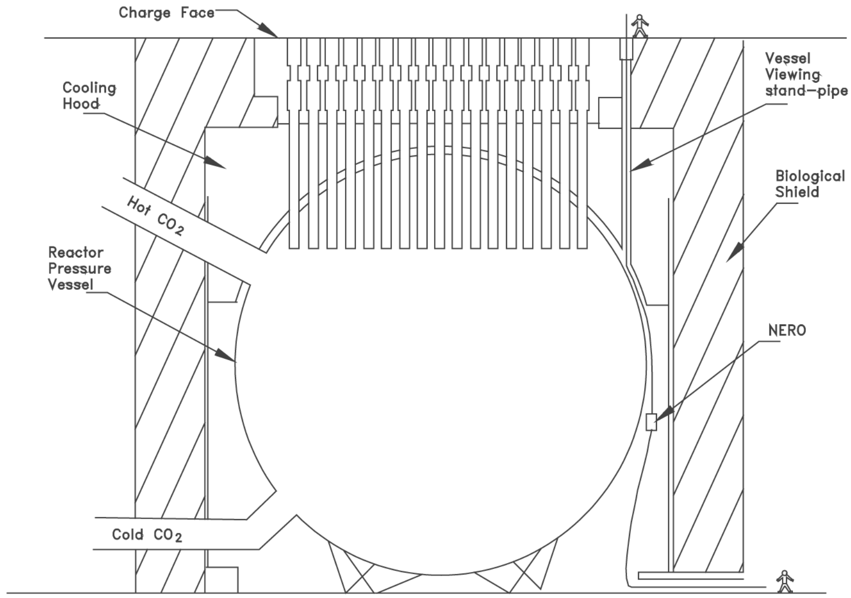
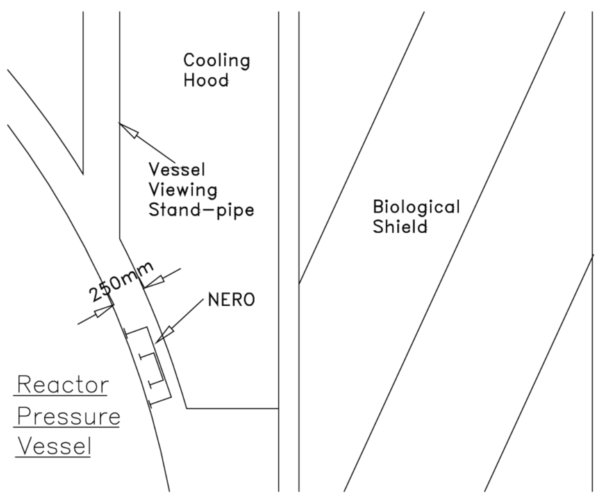
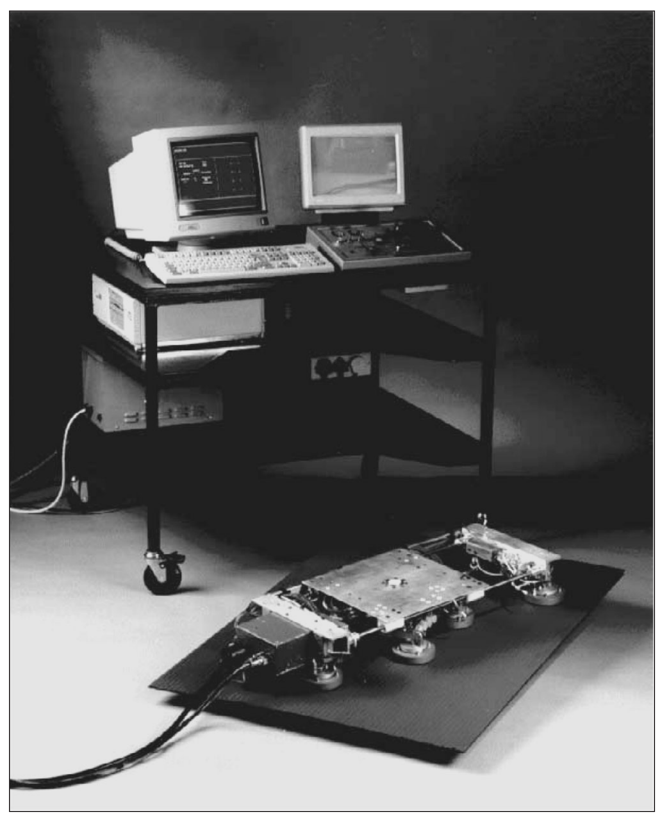


Figure 2 RPV cooling hood



be hoisted up around the equator of the RPV before it is possible to place them onto the RPV surface. The 250 mm diameter vessel viewing stand-pipe is found suitable for feeding a steel cable from the charge face to hoist the vehicles. The umbilical cable of each vehicle is also fed through the vessel viewing stand-pipe. This arrangement allows the operator to manoeuvre the position of the umbilical cable on the RPV surface and reduce the weight of the cables that the vehicle has to carry. Because of the convenience for hoisting NERO from this position, the vehicle control stations are placed on the charge face. Since, the radiation level at the entrance of the void is high, conveyor belts are set-up at each entrance for transporting the vehicles into the void. Several ground mobile vehicles are also used to assist vehicle launching. Flat metal plates are installed on top of these ground mobile vehicles and the wall-climbing vehicle is placed on this plate during launching. The whole unit is then placed

Plate 1 NERO robot and its control console



onto the conveyor. Once the ground mobile vehicle is transported inside the void by the conveyor, it carries the wall-climbing vehicle to a suitable location inside the void and the wall-climbing vehicle is then hoisted up onto RPV. Wires are attached at the rear side of the wall-climbing vehicle. These wires are also connected to ground mobile vehicles and are used to manoeuvre the wall climbing vehicles onto the surface.

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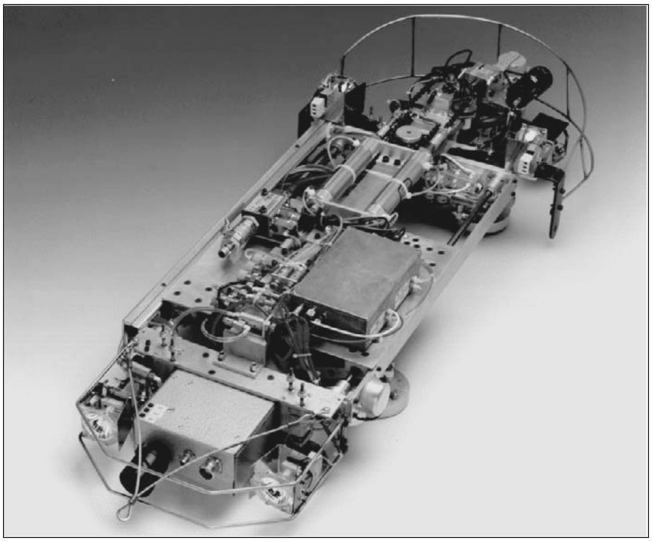
Plate 2 NERO III



Closed-circuit television cameras and lights are installed inside the void to monitor all the launching operations. Cameras can also be inserted through the vessel viewing stand-pipe. However, all these cameras can only provide images around the equator area. As soon as the wall climbing vehicle climbs above the vessel viewing stand-pipe, the monitoring will solely depend on the on-board cameras attached to the robot.

Once the vehicle has been launched onto the RPV surface, there is one operator required to drive the vehicle, one worker needed to handle the umbilical cable and one supervisor asked to oversee the operation. All the actions need to be conducted with extreme care to ensure the safety of the operations.

3. SADIE series of climbing robots

The SADIE robot is commissioned by Magnox Electric plc to perform non-destructive testing of various welds on the main reactor cooling gas ducts at Sizewell "A" Power Station. It has been determined that a vehicle similar in size ($640 \times 400 \times 180$ mm) and concept to NERO will be able to carry the necessary equipment for the range of tasks required, including pre-inspection preparation and ultrasonic weld inspection. The actual robot and its control console are shown in Plates 3 and 4, respectively. As an important part of the requirements, the robot is required to climb upside down at the top of the duct to inspect some of the welds. It is therefore necessary to develop a force controlled foot change over sequence in order to prevent the robot from pushing itself off the duct surface by exerting excessive force.

The welds which required preparation and inspection are RC24, RC25, RC26, SC12, M1, L1 and L2. These are shown in Figure 3.

3.1 Grinding application

During the initial design of the SADIE robot, it has been identified that some of the welds which require inspection are obscured by ladder brackets. As a result, SADIE is required to carry a specially designed grinding package to remove those ladder brackets. Since, the ducts are connected directly to the reactor core, it is essential that the ladder brackets should not be allowed to fall down the duct to endanger the reactor. A special grab mechanism is therefore incorporated on to the cutting tool for recovering the cut ladder-brackets. A schematic drawing is shown in Plate 5.

The ladder bracket removal package (LBRP) is mounted on the front frame of the vehicle and consists of two main elements – an air powered disk grinder mounted on a cross-

Plate 3 SADIE robot and its tool packages

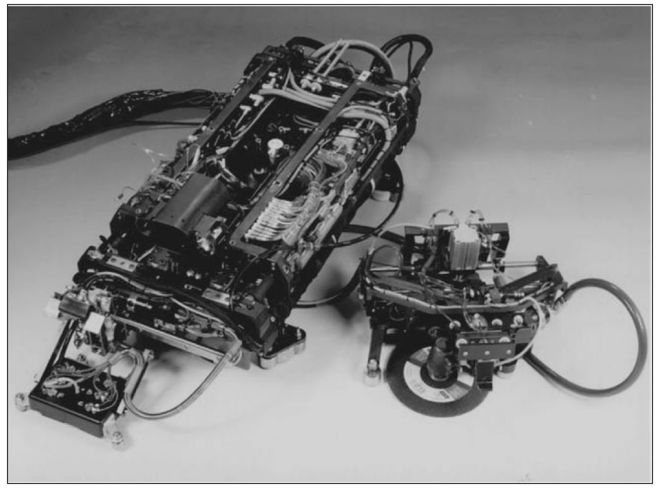


Plate 4 SADIE control console

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Figure 3 Sizewell "A" air cooling duct

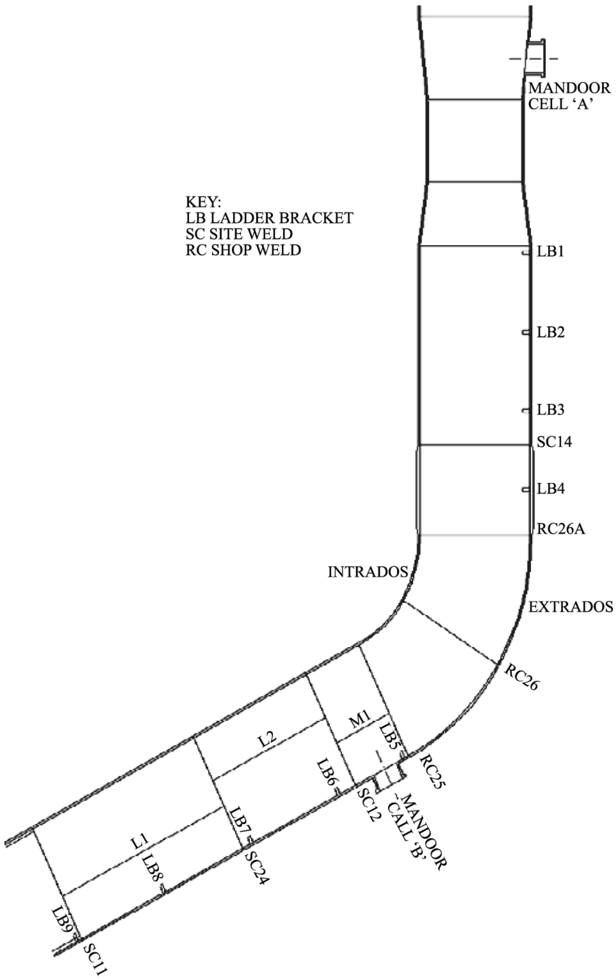
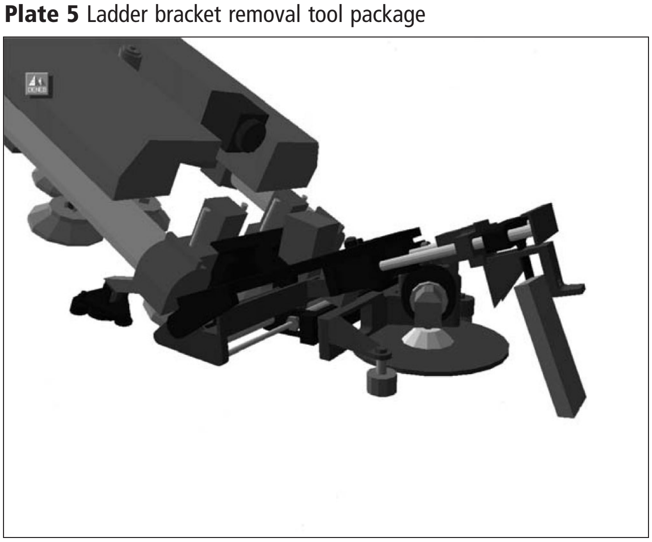


Plate 5 Ladder bracket removal tool package



feed mechanism, and a pneumatically operated grab mechanism.

The grinding tool and the cross-feed mechanism are hinged on the axis of the cross feed. A pivot allows the grinding tool and the cross feed to rotate on the cross feed axis. These degrees of freedom allow the grinder to follow the curves in the duct, providing compliance with the contours of the surface. This compliance is stabilised by ball transfer units on either side of the grinder disk and a centrally positioned pneumatic cylinder applying a steady force ensuring the transfer balls stayed on the surface. The pneumatic cylinder also provides lift to allow the grinder to be raised off the surface when manoeuvring into position. The cross feed is driven by a force controlled pneumatic cylinder.

The grab mechanism is positioned above the cross feed. The ladder bracket is held in a U bracket with a spring return piston actuating a bolt through the hole in the ladder bracket. The arm is actuated using additional pneumatic cylinders to provide a lift/lower and extended/retract functions.

The mechanism uses a camera for primary observation and micro-switches to indicate the ends of the cross fed travel. The cross feed actuators utilises a differential pressure sensor to provide force sensing.

To allow more than one ladder bracket to be removed per deployment a ladder bracket box is designed. This box is mounted on the deployment scoop. Its design incorporates a hinged lid which is kept shut with a spring. The lid traps the ladder bracket within the box.

3.2 Non destructive testing application

To inspect the welds ultrasonic scanning is used. An inspection tool has been designed by Magnox Electric for SADIE which could carry the ultrasonic transducers. An array of sensors are used in what is known as the probe pan. The probe pan uses a gimbal joint to ensure a good contact with the surface and it scans across the weld by a servo controlled linear axis mounted across the front of the vehicle.

The probe pan contains a system for squirting ultrasonic couplant around the transducers so that good quality signals are produced. The ultrasonic couplant is a water-based gel to avoid the need for cleaning the gel after the inspection.

3.3 Deployment

A major part of the operation is the deployment of the vehicle. A specially designed deployment system is constructed which comprises of a framework and a radiation containment unit. This carries the vehicle deployment scoop, deployment cable and its associated winch and the umbilical management system. The vehicle deployment scoop is a four-sided box structure, on which the vehicle is positioned prior to deployment. Its angle is controlled by a winch drive and cable.

The vehicle is placed on the deployment scoop and the vacuum is applied to the gripper feet. Having moved the frame towards the duct, the platform and vehicle are inserted through the duct access port and when the appropriate position is reached, the platform will be rotated to a vertical axis. The vehicle is then either be driven off or lifted off (having first removed the gripper feet vacuum) by the umbilical/retrieval wire onto the landing zone, at the sloping surface of the duct bend.

Retrieval is a reverse of this sequence, driving the vehicle up the duct until it is positioned on the scoop. Vacuum is then applied to cause the vehicle to attach itself onto the plate. A rotation of the scoop when it reaches the man door is executed to allow retrieval of the vehicle.

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4. Robug IIs – intelligent legged climbing service robot

Based on the aforementioned inspection tasks and also authors' other experiences in applying climbing robots for remote maintenance applications, it is found that many buildings such as nuclear RPV have very limited access. As a result, a great deal of efforts has to be made in order to launch the climbing service robots onto the buildings or structures to carry out the required inspection work. This will inevitably slow down the maintenance process and increase the risk of workers who are responsible for installing the robots. A mobile robot which has the capability of walking through a service entrance and then transferring itself onto the vertical surface of the inspected building can save time and reduce risk to human workers who may have to launch the mobile robot in difficult circumstances. In view of this, Robug IIs is developed to address the above problems. It has adopted the articulated leg structure with a thoraxial joint to achieve large reachable range and at the same time to keep its body close to the surface to reduce excessive bending moment. It has the ability to walk from the floor to the wall and is also capable of climbing over obstacles and has the intelligence to seek and verify foot-holds. This allows the robot to work in relatively unstructured environments. In order to provide a stable platform for installing tool package and carrying maintenance tasks, vacuum grippers are attached to the underside of the body in order to allow the robot to sit on the surface during maintenance operation.

4.1 Mechanical system

Robug IIs is a four limb articulated leg robot powered by double acting pneumatic cylinders. Pneumatic actuation is particularly suitable for climbing robots, due to its high force to weight ratio and inherent compliance (Collie *et al.*, 1986), which allows an elegant terrain adapting motion. The robot has adopted an endoskeletal structure; an internal frame is used to provide the required strength and stiffness for locomotion as well as locations for the joints, whilst the external actuators act as the prime mover. The advantage of using this structure is that it is more practical for fabrication and maintenance.

The robot consists of two similar modules. Each module has two mechanical legs and each leg has a vacuum gripper foot for climbing vertical surfaces. The robot also has three vacuum suckers on its underside. The two modules are joined by a pivot to form a thoraxial joint with a pneumatic cylinder to bend the body. The arrangement increases the effective moving angles of the legs and reduces the stress exerted on the leg-joints (Figure 4). This gives the robot the amount of flexibility required for the floor-to-wall transfer.

Each leg has three degrees of freedom and is organised as a spider-like structure (Figures 5 and 6). This leg mechanism provides the ability to negotiate and climb over obstacles. It also has the advantage of keeping the body close to the surface which increases the stability of the robot. An open three bar linkage mechanical structure is used to provide all three degrees of movement of each leg. The anchorage points of the hip and abductor cylinders, and the hip joint are widely separated to reduce stresses on the chassis.

The gripper foot is attached to the leg by a ball joint; this provides the gripper foot with the flexibility required to align itself with uneven surfaces. These gripper feet and the base suckers are driven by compressed-air ejector pump and can provide a pull-off force corresponding to 80 per cent atmospheric pressure.

The whole robot is shown in Plate 6.

Figure 4 Robug IIs workspace

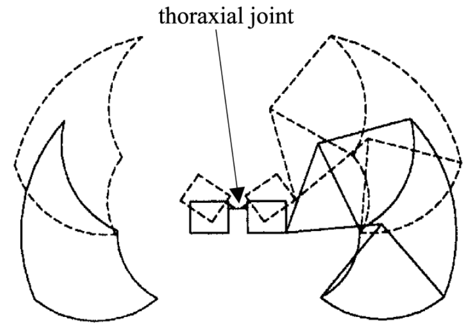

Figure 5 Plan view of the structure of the two front legs

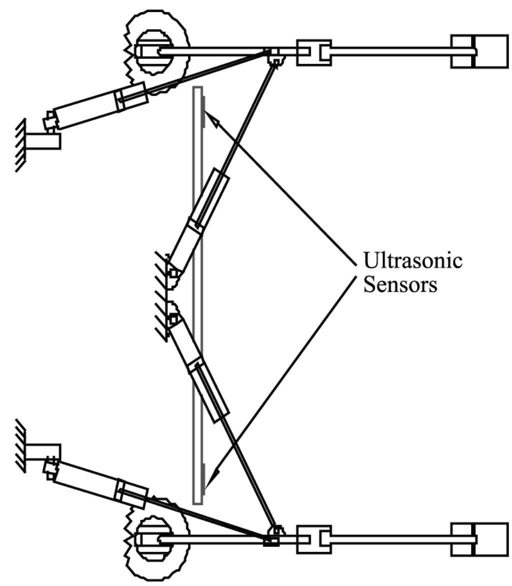

Figure 6 Elevation view of the leg structure

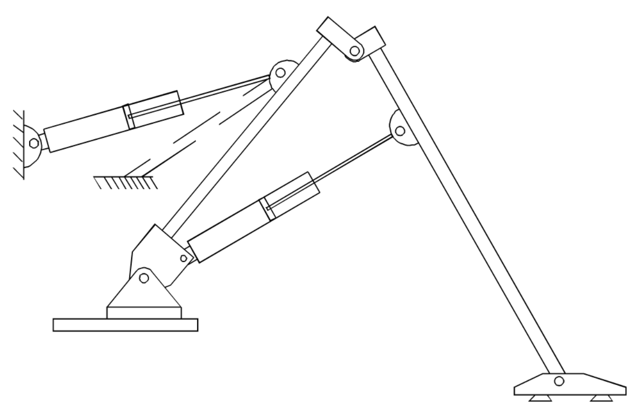

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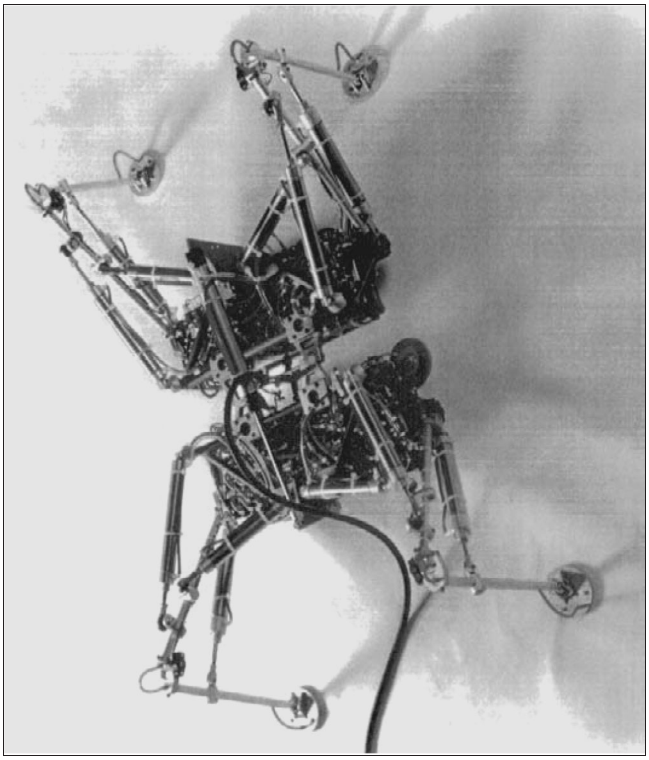
Plate 6 Robug IIs service robot



4.2 Walking and climbing movement

Robug IIs is designed to work in relatively unstructured environment. In order to accommodate the uncertainty in the working environment, Robug IIs is designed as a sensory-based control robot rather than a pure position control robot. The sensing technique used in Robug IIs is mainly tactile sensing. Each leg is equipped with pressure sensors and potentiometers to provide force and position information of the leg. The leg could be used to feel for obstacles and the level of the surface. The compliant control of the leg allows the robot to perform tactile sensing without damaging the building structure. The vacuum sensors at the feet and base suckers give the measurements of gripping force on the surface. Ultrasonic sensors are also installed at the front of the robot for measuring distance of the object. A set of reflexive rules are developed to define the behaviours of the robot for reacting to the sensory information fed back from the environment.

The walking and climbing movements of the robot can be grouped into two main types:

1. normal climbing or walking; and
2. climbing over obstacle or floor to wall transfer.

During the normal climbing or walking, the thoraxial actuator will be fully extended so that the two mechanical modules are level with each other. Base suckers are used to assist climbing and walking. In this mode, the movement of the robot can be divided into four basic steps:

1. move the legs to follow a pre-planned trajectory;
2. get the legs to grip onto the surface;
3. move the body to follow a pre-planned trajectory; and
4. get the base vacuum sucker to grip onto the surface.

When the base suckers are firmly attached on the wall, all four legs can move at the same time for fast operation.

In the case of turning, the front leg on the near side of the turning direction and the rear leg on the off side will move outward. The remaining legs will move inward. The robot will then lift the body and turn to the required direction.

For climbing obstacles or floor-to-wall transfer motions, the robot will use its thoraxial actuator to control the bending angle of the body. This increases the effective angle that the leg can travel and hence enhance the flexibility of the robot for climbing over sharp angled objects or slopes. The base suckers are not normally used in this kind of movement and only one leg is moving at any one time. Plate 7 shows the robot performing an automatic floor-to-wall transfer. More detailed information about the robot's floor-to-wall transfer motions are described in Luk *et al.* (2005).

5. Roboslave – the two arm service robot with mobile-base

Roboslave, as shown in Figure 7, is a wheel-based mobile service robot with two arms (Liu and Tso, 1999, 2000, 2002a). It is applied to nuclear plants for tasks such as handling radioactive substance, and turning off emergency valves inside a hazardous area, etc. The robot is tele-operated by a pair of hand-held robot end-effector representatives (REERs) of weight about 1 kg each (Tso and Liu, 1997,

Plate 7 Robug IIs performing an automatic floor-to-wall transfer

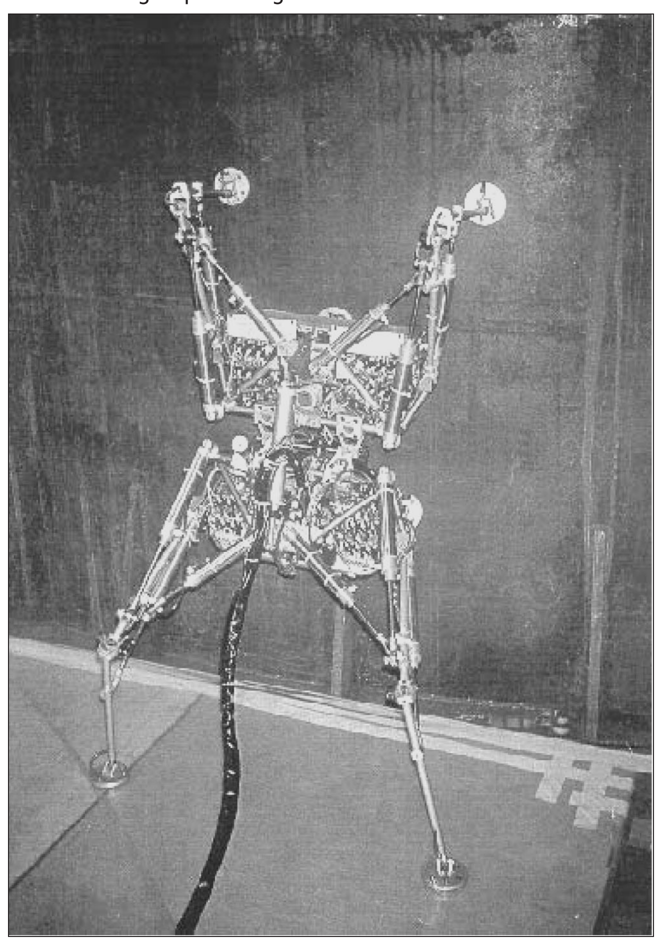
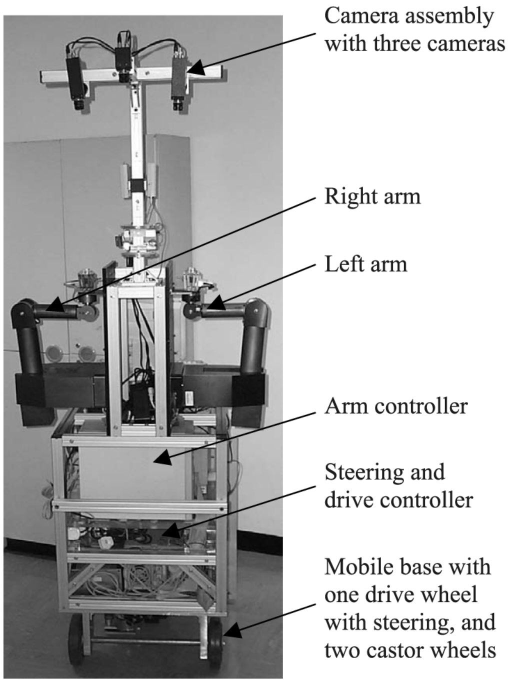


Figure 7 Roboslave – the two arm service robot with mobile-base



1998, 2003; Liu *et al.*, 2001). The operation of the system is shown in Figure 8 where human operator performs the task with the REERs in a nature way as he/she performs the job as shown in Figure 8(a) (Liu, 2002). The human demonstration is captured by a marker-based visual system, which will be discussed in Section 5.1, and the recorded information is converted to robot instruction codes (Liu and Tso, 2002b). The remote robot receives the codes and executes the task as shown in Figure 8(b). The main advantage of using REERs over the conventional encoded pair of slave arms is that one set of REER hardware equipment can instruct many different types of robot arms and manipulators provided that the information of arm dimensions are known. This section will discuss mainly the development of the REERs including the hardware design and marker calculation.

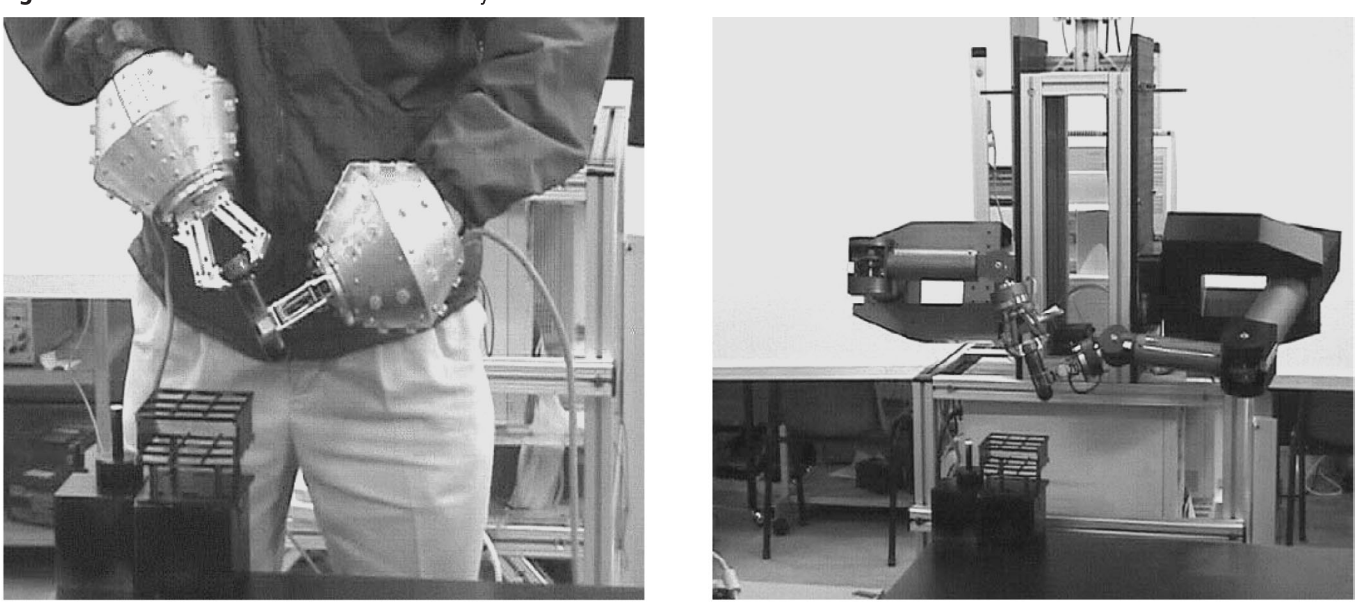
5.1 Description of the marker-based visual system

The visual system consists of four major components. They are target markers, the position sensor unit, the system unit and a host computer as shown in Figure 9. The target markers (m infra-red emitters) are installed on the rigid frame as part of one REER. The number m used depends on the rigid frame design, to be discussed in Section 5.2. The emitting beam of all markers can spread over a cone covering an approximate angle of 120° as shown in Figure 10. If the camera axis is enclosed by the beam cone, the marker is seen, and the coordinates of the marker's location can be determined. One important feature of this system is that firing pulses are applied to the markers and they are synchronized with the position sensor unit by a hardware clock. Unlike passive video systems, only one marker is seen at a time. The discrimination between markers is hence not needed.

The position sensor unit consists of three 1D cameras mounted rigidly along a strong bar. The two outside sensors have the CCD arrays aligned with the length of the bar and are angled inwards at 9°. The third sensor is mounted in the middle of the bar with its CCD array orthogonal to the other two. Each of the CCD sensors is equipped with a programmable-gain amplifier, a high-speed analogy-to-digital converter, and an on-board, dedicated RISC processor. The programmable gain compensates for the wide variation in signal strength received from the infrared markers at different distances away from the sensor unit. The on-board RISC processor is responsible for controlling the sensor unit and performing the centroid position calculation.

The system unit is a controlling, interfacing and processing unit. There is a high-speed parallel processor to handle the sequencing of the markers, and act as a link between the host

Figure 8 Instruction of the two-arm service robot by the REERs



(a) Human instruction by the REERs **(b)** Robot execution of the task

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Figure 9 Marker-based visual sensing system

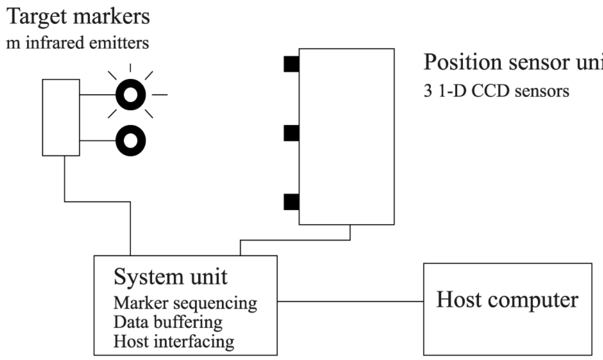
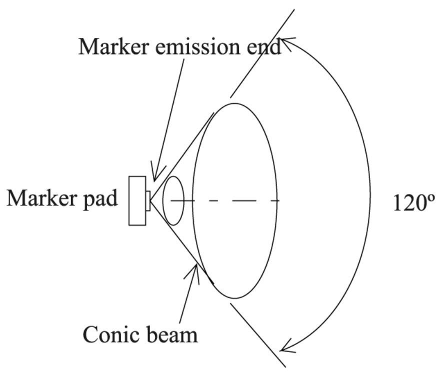


Figure 10 Emission beam of infra-red marker



computer and the position sensor unit (called hereafter the camera).

5.2 Design of the physical REER

Since, at least three marker points are required to define a rigid body, it is important to consider whether adjacent markers can be seen by the camera at the same time during the design of the REERs. For a marker to be seen, the camera axis must be enclosed by the conic beam of the marker's infrared emitter. Marker placement on the conic surface is discussed in this section to show the principle of maximizing the markers' separation and reducing the number of markers required. It is important to increase the markers' separation in order to reduce the relative error and hence to improve the accuracy of calculating the rigid body orientation.

The orientation of the conic frame is defined by the Euler angles called the yaw, pitch and roll. As intended, there is no restriction on the values of the yaw and roll angles of rotation as shown in Figure 11. However, the pitch angle is limited by the marker beam angle. In order to reduce the scanning cycle time, it is preferable to limit the total number of markers. On the other hand, the marker separation angle β in Figure 12 should be maximized. There is a relation between the half cone angle α and the angle β. Consider a marker placed at the point P and its adjacent marker placed at the point Q. The condition for the marker to be seen is that the camera axis must be enclosed by the marker beam cone.

By applying the geometric analysis (Tso and Liu, 1993), it can be proved that the maximum value of β is about 55°, and the corresponding minimum number of markers per circular track is seven. If we allow the pitch angle θ to vary from

Figure 11 Mechanical platform of one REER with markers evenly placed on circular tracks

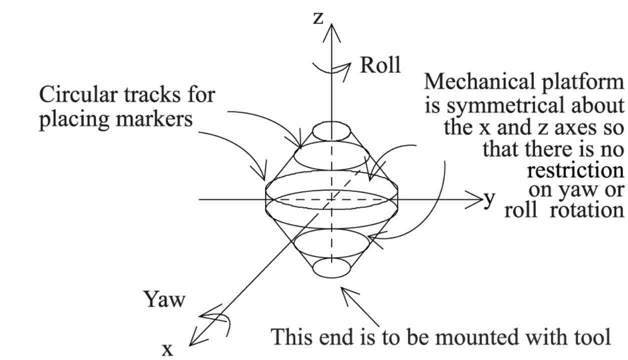
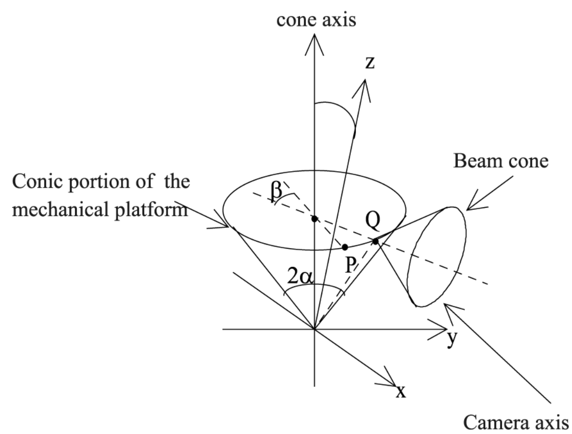


Figure 12 Diagram to define major angles in discussion



$-180°$ to $+180°$, then both the upper and lower conic units would be required. Each conic unit needs at least two circular tracks and the two units need four (Figure 11); the total number m of markers would be 28. Therefore, a pair of REERs will require 56 markers.

6. Conclusions

This paper has presented a number of leg-based climbing robots (including the NERO series, SADIE series and Robug IIs), and a wheel-based robot (Roboslave) that are designed to do remote inspection and maintenance in nuclear industry. For the climbing type robots, they use a sliding frame walking mechanism or articulated leg structure for movement. In order to allow these robots to climb on different surfaces, vacuum-gripping technology is applied. For handling uneven or rough surfaces, force information is feedback to enhance the movement controls of the legs. For the wheel-based type robot, they are applied to do more general type of work on flat floor such as handling radioactive materials insides a hazardous area. This type of general purpose service robot emphasize on the remote control applicability especially when it is equipped with two arms that involves 12 degree-of-freedom (DOF). Therefore, a pair of 6 DOF instruction tools, called REERs, is designed to facilitate this kind of tele-operation involving high DOF.

NERO robots have been used in Trawsfynydd nuclear power station for over a year and have successfully completed the required tasks; NERO II and III have effectively prepared the RPV for obstacle-free access and NERO I has successfully installed the necessary thermocouples onto the RPV. Similarly, SADIE robots (http://cidampc7.cityu.edu.hk/cidam/video/sadie.wmv – video clip showing SADIE robot in action) have been applied in Sizewell "A" Power Station for over six months, and have successfully removed all the ladder brackets which have hindered the access and carried out ultrasonic inspection on all the required welds on the cooling gas ducts. The success of the above operations is the result of the six-month extensive safety evaluation and operation rehearsals at Facility for Reactor Engineering Development (FRED) at Littlebrook. The actual implementation of NERO and SADIE robots has highlighted the need of improving the process of launching the climbing service robots onto the vertical structures to carry out the required inspection work. In view of this, Robug IIs intelligent climbing robot is developed. The robot has the capability of walking through a service entrance and then transferring itself onto the vertical surface of the inspected building. This reduces the overall effort in launching the climbing service robots for the inspection tasks. When some tasks may involve high DOF operation, such as turning off a manual valve wheel, Roboslave (http://cidampc7.cityu.edu.hk/cidam/video/roboslave.wmv – video clip showing Roboslave robot in action) with a pair of REERs has be applied to perform these types of operations.

As a whole, the climbing robots are suitable for inspecting the nuclear plant structures such as the nuclear pressure vessel, whereas the wheel-based robot is suitable to carry out tasks on flat floor. All these types of robots together can handle quite a significant portion of inspection and maintenance tasks in a typical nuclear plant. However, the costs of these robots are still too expensive for ordinary industries since they are primarily tailor-made machines. Currently, these robots are mainly applied to the situation when there is no other alternative for carrying out the work. Therefore, further effort is needed to reduce the cost of building such robots. As occupational health and safety are considered to be more and more important, it can be foreseen that these service robots will become more widely used in many different applications in the near future.

References

Bahr, B. and Yin, Y. (1994), "Wall climbing robots for aircraft, ship, nuclear power plants, sky scrapers, etc.", *Proceedings of 5th International Symposium on Robotics and Manufacturing, Hawaii, USA, August 1994*.

Briones, L., Bustamante, P. and Serna, M.A. (1994), "Wall climbing robot for inspection in nuclear power plants", *Proceedings of the IEEE International Conference on Robotics and Automation, 8-13 May*,Vol. 2, pp. 1409-14.

Collie, A.A., Billingsley, J. and Hatley, L. (1986), "The development of a pneumatically powered walking robot base", *ImechE*, c377/86 pub.

Grieco, J.C., Prito, M., Armada, M. and Gonzales de Santos, P. (1998), "A six legged climbing robot for high payloads", *Proceedings of the IEEE International Conference on Control Applications, Trieste, Italy, 1-4 September*, pp. 446-50.

Guo, L., Rogers, K. and Kirkham, R. (1994), "A climbing robot with continuous motion", *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 2495-500.

Hillenbrand, C., Berns, K., Weise, F. and Koehnen, J. (2001), "Development of a climbing robot system for non-destructive testing of bridges", *Proceedings of the 8th IEEE Conference on Mechatrinics and Machine Vision in Practice, Hong Kong, 27-29 August*, pp. 399-403.

Hirose, S., Nagakubo, A. and Toyama, R. (1991), "Machine that can walk and climb on floors, walls and ceilings", *Proceedings of the International Conference on Advanced Robotics, 19-22 June*.

Kroczynski, P. and Wade, B. (1987), "The skywasher: a building washing robot", *Proceedings of the 17th International Symposium on Industrial Robots*,Vol. 1, pp. 11-19.

Liu, K.P. (2002), "Two-arm service robot programming through automatic capturing of human skill and intention as demonstrated by hand motion", PhD thesis, Department of Manufacturing Engineering and Engineering Management, City University of Hong Kong, Hong Kong, PRC, September.

Liu, K.P. and Tso, S.K. (1999), "Programming a two-arm service robot for improved manipulability", *Proceedings of the Workshop on Manipulation for Intelligent Automation, Hong Kong, September*, pp. 76-81.

Liu, K.P. and Tso, S.K. (2000), "Two-arm service-robot programming by human demonstration using skill-capturing devices", *Proceedings of the Workshop on Service Automation and Robotics, Hong Kong, June*, pp. 181-91.

Liu, K.P. and Tso, S.K. (2002), "Application of hidden markov model to mapping of typical human hand motion types for automatic programming of service robots", *Proceedings of the 4th Asian Control Conference, ASCC, Singapore, September*, pp. 1273-8.

Liu, K.P. and Tso, S.K. (2002), "Trajectory segmentation approach for vision-based learning of human instructions by service robots", *Proceedings of the 4th Asian Control Conference, ASCC, Singapore, September*, pp. 954-9.

Liu, K.P., Tso, S.K. and Luk, B.L. (2001), "Sensor-based supervisory master-slave operation of robots", *Proceedings of the 32nd ISR (International Symposium on Robotics), Seoul, Korea, April*, pp. 556-61.

Luk, B.L., Cooke, D.S., Galt, S., Collie, A.A. and Chen, S. (2005), "Intelligent legged climbing service robot for remote maintenance applications in hazardous environments", *Journal of Robotics and Autonomous Systems*, Vol. 53/2, pp. 142-52.

Nishi, A. (1996), "Development of wall-climbing robots", *Journal of Computers Elect. Engng*, Vol. 22 No. 2, pp. 123-49.

Pack, R.T., Christopher, J.L. and Kawamura, K. (1997), "A rubbertuator-based structure-climbing inspection robot", *Proceedings of the IEEE International Conference on Robotics and Automation, Albuquerque, New Mexico, April*, pp. 1869-74.

Sato, K., Honda, K., Haegawa, A., Shiota, T. and Morita, H. (1991), "On-wall locomotive vehicle", *ISART.*

Sattar, T.P., Alaoui, M., Chen, S., Bridge, B. and magnetically, A. (2001), "A magnetically adhering wall climbing robot to perform continuous welding of long seams and non-destructively test the welds on the hull of a container ship", *Proceedings of the 8th IEEE Conference on*

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Mechatrinics and Machine Vision in Practice, Hong Kong, 27-29 August, pp. 408-14.

Tso, S.K. and Liu, K.P. (1993), "Visual programming for capturing of human manipulation skill", *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Yokohama, Japan, July*, pp. 42-8.

Tso, S.K. and Liu, K.P. (1997), "Demonstrated trajectory selection by hidden markov model", *Proceedings of the IEEE International Conference on Robotics and Automation, Albuquerque, New Mexico, USA, April*, pp. 2713-8.

Tso, S.K. and Liu, K.P. (1998), "General representation of human demonstration using differential-geometry properties", *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Victoria, Canada, October*, pp. 1950-5.

Tso, S.K. and Liu, K.P. (2003), "Opto skill capturing and visual guidance for service robots", *Opto-Mechatronic Systems Handbook Techniques and Applications*, CRC Press, LLC, pp. 20-1-20-33.

Tso, S.K., Fung, Y.H., Chow, W.L., Zong, G.H. and Liu, R. (2000), "Design and implementation of a glass-wall cleaning robot for high-rise buildings", *Proceedings of the World Automation Congress Eighth International Symposium on Robotics with Applications, Maui, Hawaii, June 11-16*, paper ID: ISORA123.

Tso, S.K., Zhu, J. and Luk, B.L. (2001), "Prototype design of a light-weight climbing robot capable of continuous motion", *Proceedings of the 8th IEEE Conference on Mechatrinics and Machine Vision in Practice, Hong Kong, 27-29 August*, pp. 235-8.

Wang, Y. and Shao, H. (1999), "Wall climbing robot for cleaning and painting", *Proceedings of the 2nd International Conference on Climbing and Walking Robots, Portsmouth, UK, September*.

Zhang, Q.X., Ren, Z.G. and Zhao, Z. (2001), "Development of a 3W window-cleaning robot for high-rise buildings", *Proceedings of the 8th IEEE Conference on Mechatrinics and Machine Vision in Practice, Hong Kong, 27-29 August*, pp. 257-60.

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