2020 16th IEEE International Conference on Automation Science and Engineering (CASE)
August 20-21, 2020, Online Zoom Meeting

Review of Classification for Wall Climbing Robots for Industrial Inspection Applications

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Abstract— **A new methodology that mixes the already well-established classifications of Wall Climbing Robots (WCR) based on locomotion and attachment is proposed. The need for industrial inspections of processing assets, with vertical flat surfaces, like tanks and pressure vessels that are continuously exposed to fatigue, corrosion and erosion are identified. The types of industrial inspections tasks vary in a wide range from, Visual Inspections (VI) and Non-Destructive Testing (NDT) to cleaning and repair. Mobile robots are used to perform inspection tasks. There are few commercial WCR that are available for industrial applications. The classification method is based on locomotion mechanisms, and attachment techniques rather than classical classification assumed in all previous reviews of WCR. A general design framework is suggested to derive the custom-building design of the inspection WCR. The performance of the WCR is compared against the main features of maximum speed and payload capacity. The main locomotion types are wheeled (W), tracked (T), walking (L) and hybrid (H). The primary attachment methods are magnetic (G), pneumatic (P), mechanical (M), electrostatic (E), chemical (C) and hybrid (H). As another application, the classification is used to identify and differentiate WCR from other types of Climbing Robots (CR) to cover almost all kinds of WCR. In addition, the classification can be employed in the customisation of WCR that are built to perform specialised inspection tasks. The customisation of WCR results from the need for simplicity in their structure, adapting testing equipment and improving operations.**

I. INTRODUCTION

Robots are used nowadays in different industries such as manufacturing, construction and inspection [1]. Industrial robots are now capable of performing various tasks and movements across one, two or more axes [2]. Applications of industrial robots include, but not limited to, assembling, picking, placing, welding, painting, packaging, labelling, palletising, inspecting, and testing [3]. Robots have a reputation for performing tasks at high speed and with precision [4]. Wall Climbing Robots (WCR) are types of mobile industrial robots that can ascent/descent vertical or inclined walls [3], [5]. WCR are used to perform inspections, cleaning and maintenance tasks, where access to the work location is an issue or a hazard [6]. Recent developments in software, sensors and cameras have empowered robots to perform visual inspections with an efficiency that is comparable with a human; sometimes with higher precision [5].

Climbing Robots (CR) are robots that are capable of ascent and descent over rough terrain, stairs, trees, cables and any other objects [1]. Thus, WCR are a subsection of CR. WCR are robots that are capable of ascending and descending vertical surfaces freely using adhesion [7], whereas CR usually lack an attachment method. The main feature of WCR is that they have the ability to climb walls and vertical surfaces freely, without external assistance [8]. On the other hand, CR can only climb on objects, e.g. poles or trees, and not only vertical flat surface [7]. The adhesion or attachment method is the second feature that is associated with the WCR [3]. Differentiation between CR and WCR is vital for identifying the capability of a robot to climb vertical flat surfaces and walls. Moreover, the division makes it easy for the industry end-user to categorise the requirements for the use of CR or WCR.

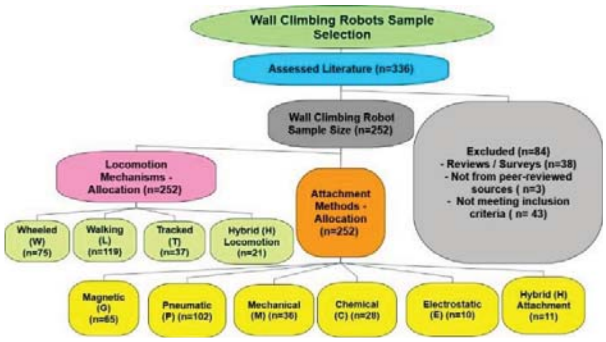

Figure 1 - Sampling flow chart

Over the last five years, many research papers have been published addressing the issue of WCR [1], [3]. Most of the published literature has presented the development of new WCR [5]. Professional and industrial conferences are held every year to present the developments in the industry. The IEEE robotics and automation conferences are the most public events for presenting new inventions in WCR [9]. The climbing and walking robot association (CLAWAR) also has an annual conference, which specialises climbing robots funded by the European Union (EU) [7]. The global industry

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initiatives and the academic literature both demonstrate the level of increased interest in WCR [10].

Petrobot® is a joint-industry project facilitated by oil operators and funded by the EU, which aims to develop inspection robots to reduce human exposure to risky areas [11]. The development of the market for climbing robots designed for specific end-users by GE® [12], [13] and others is another indication of the increased level of interest and high market demand. Until now, there have been limited numbers of commercially available WCR for asset integrity inspections [6]. GE® Bike platform, which was built based on the work by Tâche [14], is the most common commercial WCR available that provides such services. Invert Robotics® have also introduced a new crawler robot for inspection services. The robot is a tracked-pneumatic (TP) type of WCR [15]. There are other manufacturers, but there are no other notable WCR in the industry.

There are several surveys and reviews of WCR [1], [3]–[5], [8], [16]–[18]. Most of the reviews that were studied, [1], [4], [5], considered translation/sliding frames as a category, and did not include hybrid (H) locomotion mechanisms as a category. Hybrid locomotion is when two or more of the main mechanisms are combined [1]. In [8], researchers considered legged as one category, and arms or actuators as another category. The classifications by [8] are representative of a wide range of WCR. The work in [19] presents a great breakdown of attachment methods, yet did not include the hybrid (H) attachment method. The bio-inspired attachment methods are mainly mechanical (M) or chemical (C), as such fall under mechanical and chemical attachment methods. Some classification did not include several essential types of attachment methods [3]. The work of [1], [3], [18] classified rope/rail-guided as an attachment method.

II. METHODOLOGY

Replicability and reproducibility are primary concerns for academics in the robotics industry. Good Experimental Methodology (GEM) and benchmarking were introduced into robotics research to improve robotics research outcomes [20], [21]. This paper follows the GEM for robotics research. It presents a statistical sample of the available prototypes and literature to create a broad study of WCR [1]. Then, each type and class are reviewed in depth for detail, richness and completeness. Industry standards and scientific methodology are applied throughout the research [22].

Literature and prototype samples for 336 WCR (n=336) were collected. Some samples (n=84) were excluded from the population being studied. Reasons for exclusion include the literature not stemming from peer-reviewed sources (n=3), or not meeting inclusion criteria (n=43) (refer to Figure 1). Examples of excluded samples are pole climbing robots, step/stair climbing robots, terrain climbing robots and mobile robots. The samples that were included in this study are (n=252). The sample represents the development of WCR over the last 30 years, as depicted in Figure 2. The WCR main features of the WCR were studied. The sample population was analysed based on the collected information, to the best of the authors knowledge.

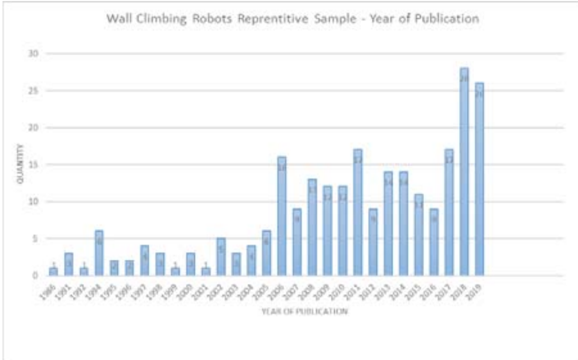

Figure 2 - WCR representative sample - year of publication

III. WCR CLASSIFICATION

The developed WRC presented in the representative sample have been experimented with various locomotion mechanisms and a wide range of attachment methods. Each WCR can be classified by its locomotion mechanism and adhesion techniques, as follows:

A. *Classification based on locomotion mechanisms:*

The locomotion mechanism is the mobility technique that enables mobile robots move in their environment.

- *Wheeled (W) Mechanism*

A wheeled (W) mechanism is a wheel-driven robot, which obtains mobility by rotating its wheels over a surface. The types are fixed standard wheels, steered standard wheels, castor wheels, Swedish wheels and spherical wheel models and constraints; differential-drive, omnidirectional and number of wheels [10].

- *Tracked (T) Mechanism*

A tracked (T) mechanism is a track or crawler driven robot, which obtains mobility by sliding its tracks over a surface. Steering is accomplished by slipping or skidding [4]. Crawler types are non-articulated tracks or articulated tracks. Tracked WCR are well known for causing damage to surface coatings or insulation when turning [23].

- *Walking (L) Mechanism*

A walking (L) mechanism is a legged, armed, tailed, manipulators or gripper-driven robot, which obtains mobility by taking steps. Walking WCR have high degrees of freedom (DOF) [5]. Examples are one leg, two legs (biped), four legs (quadruped) and six legs (hexapod) [5].

- *Hybrid (H) Locomotion Mechanism*

A hybrid (H) locomotion mechanism is any combination of the primary locomotion mechanisms, wheeled, tracked or walking, used by a mobile robot to obtain mobility. The hybrid locomotion mechanism combinations can be wheeled-tracked (WT), wheeled-walking (WL), tracked-walking (TL) and wheeled-tracked-walking (WTL) [24]. Hybrid robots are famous for a blend of wheeled walking (WL), combining the adaptability of walking with the efficiency of wheeled locomotion to offer excellent manoeuvrability.

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B. Classification based on Attachment Methods:

- *Magnetic Method (G)*

The magnetic (G) attachment method uses the magnetic adhesion force from a permanent magnet or electromagnet to attaching to ferromagnetic surfaces. They have good energy efficiency. Non-contact magnetic adhesion is a method where the magnets are not in contact with any surface while achieving the desired attachment force [25].

- *Pneumatic Method (P)*

The pneumatic (P) attachment method utilises pneumatic force for adhesion. The pneumatic adhesion force can come from suction cups (passive and active) or negative pressure-thrust to attach to the desired surfaces [26].

- *Mechanical Method (M)*

The mechanical (M) attachment method utilises a gripping force for adhesion. The gripping adhesion force can come from grasping hands, tiny toes, claws or spines, hooks, friction, microscopic hairs, fibres arrays, small needles, grasping, gripper or tail to attach to the desired surfaces [19].

- *Electrostatic Method (E)*

The electrostatic (E) attachment method uses a novel compliant electro-adhesion force for adhesion. The electrostatic adhesion force comes from an electrically controlled electrostatic attraction to attach to the desired surfaces [27].

- *Chemical Method (C)*

The chemical (C) attachment method utilises a molecular polarity force for adhesion; either wet or dry. The chemical adhesion force can derive from glue, thermal glue, sticky tape, magnetorheological fluids or elastomeric adhesion to attach to the desired surfaces [28].

- *Hybrid Attachment Method (H)*

The hybrid (H) attachment method uses a combination of any of the primary attachment methods (magnetic, pneumatic, mechanical, electrostatic or chemical) of the WRC to attach to the desired surfaces. There are twenty-six different combinations of the main five attachment methods [1].

C. WCR TYPES

The new classification system being introduced, covering locomotion mechanisms and attachment methods, generates 24 types of WCR. A one-letter code was assigned to each locomotion mechanism with attachment methods. The new 24 types of WCR work by combining both letters. Refer to Table I for the full list. For example, WCR type LE is a walking robot with an electrostatic attachment method.

IV. DATA AND RESULTS

In Table I, a colour gradient scale was used to represent the number of robots of a specific type for visual illustration. The most significant number of prototypes falls under the LP Type, walking-pneumatic, making up 22.6% of the sample population. The wheeled (W) prototypes are 29.8% of the sample population, while 14.7% are tracked (T), 47.2% are walking (L) and 8.3% are the hybrid (H) locomotion type. On the other hand, the percentages of the prototypes based on attachment methods are 25.8% magnetic (G), 40.5% pneumatic (P), 14.3% mechanical (M), 4.0% electrostatic (E), 11.1% chemical (C) and 4.4% are the hybrid (H) attachment types.

TABLE I
NUMBER OF WCR IN THE LITERATURE/PROTOTYPE

Attachment / Locomotion	G	P	M	E	C	H	Total
Wheeled (W)	38	30	2	0	4	1	75
Tracked (T)	18	8	0	5	4	2	37
Walking (L)	5	57	34	5	15	3	119
Hybrid (H)	4	7	0	0	5	5	21
Total	65	102	36	10	28	11	252

The main features of the payload capacity and maximum speed of the WCR in this paper were studied. Table II shows a comparison of the payload capacity and maximum speed for the different locomotion mechanisms. Maximum values were utilised because they represent the maximum capacities that researchers have achieved, using the maximum values obtained from the prototype robots that were in the collected samples.

TABLE II
COMPARISON OF LOCOMOTION MECHANISMS

Locomotion Mechanisms	Payload Capacity (kg)	Speed (mm/s)	Comments
Tracked (T)	100.00	250.00	Larger surface contact area, complex surfaces, normally heavy, low/limited steering capacity, difficulty in turning to avoid obstacles
Wheeled (W)	80.00	320.00	Fast and continuous locomotion, even surfaces, small contact area, skid easily, weak adaptation when avoiding obstacles
Walking (L)	100.00	670.00	Work in very rough and steep terrain, complicated controls and structures, imprecise movements, low speed
Hybrid (H)	40.00	2,000.00	Continuous locomotion, high redundancy

The speed at which the WCR travels mainly depends on the locomotion mechanism. The locomotion mechanisms contribute more to travel speed than to payload capacity. From Table II, hybrid (H) locomotion has the highest maximum travel speed of 2000 mm/s, whereas the minimum travel speed is found with the tracked (T) WCR at 250 mm/s. Conversely, when comparing the payload capacity based on the locomotion mechanisms, the highest payload capacity went to tracked (T) and walking (L). Hybrid (H) locomotion obtained the lowest payload capacity of 40 kg. Wheeled (W) locomotion was not very far from the maximum but double the minimum with 80 kg.

TABLE III

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COMPARISON OF ATTACHMENT METHODS

Attachment Methods	Payload Capacity (kg)	Comments
Magnetic (G)	100.00	Suitable for ferromagnetic walls only, no energy required for attachment, great attachment force
Pneumatic (P)	100.00	Impractical for uneven walls, sealing issues, large energy consumption, noise, great attachment force
Mechanical (M)	20.00	No power is required, not suitable for smooth and flat walls
Electrostatic (E)	1.40	Simple, enhanced adaptability, effective in dusty environments, adheres to both conductive and insulating materials, external power required
Chemical (C)	0.51	Micro or nano Robots, very sensitive to dust, Small attachment force, does not require energy, small pay load
Hybrid (H)	10.00	Not enough detail available for evaluation

The attachment methods mainly affect the payload capacity of the WCR. When the payload capacity of the different attachment methods are compared, in Table III, the maximum was the magnetic (G) and the pneumatic (P) together in first place with a 100 kg payload capacity. The lowest, unsurprisingly, was the chemical (C) attachment method, due to its high sensitivity to dust and the environment, with a 0.51 kg. The electrostatic method (E)was not very far from the minimum, with a 1.40 kg.

TABLE IV
COMPARISON OF THE TYPES OF WCR

WCR Types	Number of Prototypes	Max Weight (kg)	Max Payload Capacity (kg)	Maximum Speed (mm/s)
HC Type	5	0.09	0.10	60.00
HE Type	0	NA	NA	NA
HH Type	5	1.90	NA	350.00
HG Type	4	750.00	15.00	340.00
HM Type	0	NA	NA	NA
HP Type	7	10.00	40.00	2,000.00
LC Type	15	0.63	0.20	300.00
LE Type	5	0.33	1.00	6.60
LH Type	3	2.19	5.32	1.00
LG Type	5	220.00	100.00	200.00
LM Type	34	26.00	20.00	670.00
LP Type	57	72.00	100.00	100.00
WC Type	4	0.17	NA	25.00
WE Type	0	NA	NA	NA
WH Type	1	24.00	1.00	37.00
WG Type	38	97.00	80.00	320.00
WM Type	2	0.50	1.25	100.00
WP Type	30	200.00	10.00	300.00
TC Type	4	0.18	0.51	120.00
TE Type	5	1.27	1.40	100.00
TH Type	2	6.40	10.00	220.00
TG Type	18	100.00	100.00	116.67
TM Type	0	NA	NA	NA
TP Type	8	70.00	42.00	250.00

V. APPLICATIONS OF WCR IN THE MINING AND PETROLEUM INDUSTRIES

The areas where the WCR can be utilised are as broad and varied as their applications. The introduction of the design framework helps in narrowing down the application areas [22]. As a result, identification of the assets and tasks that are to be performed by WCR will make it easy for the designer to select its desirable features [29]. Finally, after identifying the necessary qualities of the WCR, the selection of the locomotion mechanism and attachment method will result in a WCR that performs the required tasks efficiently [23].

A. Design Framework

The design framework of each WCR involves many variables and feature options. A WCR is a complex system. As such, a weighted factors matrix, such as the one in [22] will make it simpler for the designer to quantify the necessary qualities of the WCR. Qualitative analysis is required to specify the features of the WCR. This paper focuses on most of the desired features and relevant applications.

A WCR type, from a control point of view, can be autonomous or tethered. An autonomous WCR can navigate itself over the equipment surface in a back and forth motion to perform the task on the desired wall to find possible faults using sensors without any human intervention [2]. The main disadvantage of autonomous WCR is the difficulty in developing highly accurate inspections mapping, as the WCR position is estimated with a large margin of error [2], [7]. The other types are the tethered WCR, which uses an umbilical cable and is controlled by an operator, and the semi-autonomous WCR, where an operator uses a remote control to control the WCR [5].

Localisation and autonomous navigation of WCR are of paramount importance to industrial applications. The accuracy of detecting the location of a faulty surface is complex and crucial for the industry [6]. Inaccurate reporting of the exact spot where a repair is required costs industry significantly in terms of wasted time and resources. There are many systems available to overcome the localisation problem. Simultaneous Localisation and Mapping (SLAM) is one of the key navigation techniques. SLAM generates a recollection of perceptions into an environment map. Absolute localisation relies on landmarks, maps, beacons, or satellite signals to determine the WCR global position and orientation. Surface coverage algorithms, based on distance, transform this function [6].

Data processing and communications, advanced data processing algorithms, obstacle avoidance and adaptation to

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surface curvatures are crucial for WCR to operate on different types of structures [1].

B. *Inspection Tasks*

Inspections of assets in industrial facilities are the most time-consuming activities undertaken. Inspections are regular and continuous. The repetitiveness makes the process easy to automate. WCR are the best candidates for automation of inspection tasks [24].

- Visual Inspections (VI)

Video streaming, close-up images, and a combination of these are types of VI used to produce spatially and time-tagged data of the inspection. Another kind of VI is the Borescope inspection, where a small camera with a light attached to a rigid or flexible tube is used to inspect inaccessible areas. VI is used to take test images, detect cracks, investigate visual damage, engage with visual corrosion detection and evaluate structural health conditions [6]. The primary desired features of WCR for visual inspections are higher maximum speeds, being lightweight, alongside having high adaptability to access narrow spaces and autonomy with high-resolution real-time data transfer [8], [23], [26].

- Non-Destructive Testing (NDT)

Conventional inspection techniques for NDT are Ultrasonic Testing (UT) like Phased Array Ultrasonic Testing (PAUT), Time of Flight Diffraction (TOFD), Radiographic Testing (RT) and Eddy Current Testing (ECT). The NDT is of paramount importance to the industry as it is used to detect failures and defects in assets [23].

The primary, most-anticipated quality of WCR for NDT inspections is a higher payload capacity so that the robot can carry inspections tools. Another desired quality is localisation and positioning of the WCR, to map the NDT area accurately [23]. In addition, autonomy with high-resolution real-time data transfer is sought after [6].

- Leak Testing and detecting

Hydro and leak testing are among the most common forms of testing in industrial facilities. Helium is used for leak testing of gas tanks. WCR can be used to determine the position of leaks [4].

C. *Cleaning and wash down Tasks:*

Cleaning of assets is essential to maintain their efficiency. Cleaning is performed during regular operations and inspections. Cleaning can be undertaken using the following methods [3]. Washing assets with potable water is a common practice. The washing keeps assets clean and in good operational shape [1].

- Abrasive blasting

Grit or abrasive blasting is used for cleaning and stripping assets' surfaces from coatings, rust or dirt. The process of blasting is performed using small particles of sand, grit or metals through a high-pressure fluid, generally air or water [4].

- Water Jetting

With the introduction of new environmental regulations, the use of water jetting is becoming more common. Ultra-high-pressure water-jetting is becoming an alternative to conventional abrasive blasting. The efficiency of water jetting is still being questioned by industry [6].

D. *Welding and Repair:*

- Automatic Welding

Welding WCR will enhance the quality of welding, saving time, and eliminating hazards. The WCR must be equipped with industrial welding units and high-quality seam tracking sensors [18].

- Repairing

Conducting repairs onsite saves the industry much time and money. Having a WCR to repair in-situ will improve the process drastically. Repairs are complex and challenging activities, as they usually deal with cleaning, gouging, grinding, welding, measurement and coating [24].

- Dismantle and assembly

Dismantling and assembly processes are sophisticated activities that are challenging to the robotics field. They require the design of manipulators with excellent motor skills, multiple cameras and grippers.

VI. CONCLUSION

A new classification system for WCR that covers almost every type was introduced. The classification of WCR based on locomotion mechanisms: wheeled (W), tracked (T), walking (L) and hybrid (H). Classification based on attachment methods fall into magnetic (G), pneumatic (P), mechanical (M), electrostatic (E), chemical (C) and hybrid (H). The new method covers all the known attachment methods and based on a scientific approach. Twenty-four types of WCR were identified. Robotics researchers may use these types to identify, combine and cherry-pick suitable the desired locomotion and attachment method to suit a specific application of a WCR. This paper focused on a comprehensive standardised classification system [7]. The innovative adhesion methods necessitate broader categorisation systems, using generic scientific classifications [28], instead of WCR being classed as per biological systems or customised categories. The performance of each WCR type in maximum speed and payload capacities has been reported. A generalised design framework, which includes qualitative and quantitative analysis from [22], was proposed for a baseline to specify the requirements and needs of the WCR.

Hybrid systems are expected to outperform any single method of locomotion or attachment. The hybrid systems combine the advantages of each specific system [4] as well as overcoming the limitations of every individual system [24]. Hybrid WCR, in terms of both locomotion and attachment, in general, are not yet explored, so further work is required to develop more reliable hybrid WCR to cover the industry requirements [12], [13]. Presently, we are working on a review

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of hybrid CR, which will provide more options in designing hybrid CR and will report on the performance of hybrid CR against single system CR. The magnetic attachment method still suffers from efficiency reductions due to the accumulation of debris and rust on the magnet [4]. Research and development of an effective system of removing rust and debris are required [25]. The pneumatic attachment of the vortex type is vulnerable to damage and reduced efficiency due to fan exposure to debris sucked through with air [26]. The chemical attachment method requires further research to improve the sensitivity to surface condition, increase the payload capacity and be used in applications for bigger sizes of WCR [28].

The recent developments in the electrostatic (E) attachment method make it an ideal candidate for solving all of the industry challenges, yet it is not well developed [5], [28]. When it reaches industrial readiness maturity level, electroadhesion will cater to industrial applications more than any other attachment method [27]. There are several reasons for that. First of all, it is capable of adhering to any type of surface with different roughness's [16]. Secondly, although the attraction force depends on high voltage, the consumed current is very low, so low power consumption [17], [27]. Let alone, the simplicity of the components, spontaneous attachment/detachment skills [27], low weight and small dimensions [16] and low decibel (dB) levels [17]. Finally, it works effectively in dirty environments, with no decreased adhesion due to dust and rust [27], [28]. Currently, we are working on a novel modelling of electrostatic (E) attachment force for interdigital (comb) arrangement electroadhesive pads in WCR, which will be reported in a future paper.

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