American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)

ISSN (Print) 2313-4410, ISSN (Online) 2313-4402

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http://asrjetsjournal.org/

Confined Spaces: Cleaning Techniques and Robot-based Surface Cleaning

Kinan Dandan[a]*, Houssam Albitar[b], Anani Ananiev[c], Ivan Kalaykov[d]

[a,b,c,d]School of Science and Technology, Orebro University, 70182, Orebro Sweden

[a]Email: kinan.dandan@oru.se

[b]Email: houssam.albitar@oru.se

[c]Email: anani.ananiev@oru.se

[d]Email: ivan.kalaykov@oru.se

Abstract

The requirements of the working and safety norms demonstrate significant need of increased efficiency and improved working conditions in cleaning confined spaces. This paper presents an overview of the existing technologies and solutions for cleaning large confined spaces. A special attention is directed for cleaning interior surface of confined spaces used mainly for storing bulk materials or liquids, such as silos. The cleaning technologies for confined space depend on several aspects as the build-up material, the surface material, the ambient conditions. Four cleaning techniques are presented in this paper. The mechanisms and robots related to the studied problem are surveyed and evaluated from the viewpoint of their capability to clean interior surfaces. The dominating majority of the existing cleaning equipment is constructed to serve cleaning the entire volume of the respective confined space (silo), but not for cleaning the interior surface.

Keywords: Confined space; silo; surface cleaning; cleaning technologies; cleaning robots.

1. Introduction

Working conditions inside confined spaces for cleaning surfaces are often extreme and workers need overall protection with tight clothing, helmet, face mask, earmuffs, and respirator. It's dirty, noisy with bad sight and heavy with high static work load. Accident risks are obvious.

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* Corresponding author.

The law about working environment does not permit that work of this kind is carried out for longer time than 30 minute periods. In reality unfortunately this period is not respected. Plants and equipment are seldom or never built to be cleaned and sanitized efficiently.

The work is of the same reason characterized by inefficiency and without other quality control than the performer's subjective judgement.

Implementing robots or automated mechanism for doing the cleaning works in such hazardous spaces depend on the size and the material of confined space, the stored materials, the type of cleaning technique, and the sort of cleaning. Developing a cleaning robot inside confined space should be able to bear several challenges the roughness of interior surface, the movability in large space, safety and reliability of the attachment to the interior surface, and the efficient cleaning.

This paper will analyze the working conditions in cleaning and assessment of large confined spaces such as silos, large tank, in section 2. Section 3 investigate, review and analyse the applied technologies and respective equipment for cleaning. Section 4 presents robot-based technology for cleaning large confined spaces. Section 5 shows in which way certain design aspects lead to a highly sophisticated cleaning robot for large food silo. Finally, section 6 address concluding remarks.

2. Confined spaces

Reams of documents and procedures have been written by states and corporate safety departments on how to define a hazard environments, and safety rules which should be strictly respected by the workers and the organizations when performing some sort of cleaning, maintenance or repair operations.

A confined space is defined as a partially or fully enclosed space, and has the following characteristics [1]:

- A wide enough inside area in which the worker can work into, but not intended as a place of work.
- A difficulty in entrance or exit the space, which depends on the size and the location of the hole.
- A normal atmospheric pressure.
- Atmospheric and physical hazards.

According to the above definition, structures such : vat, tank, pipe, silo, vessel, container, boiler, or tunnel, are considered as confined spaces.

Hazards in confined space: some hazards may be present regarding to the type of substance previously stored in the confined space, other hazards may arise from process and work activities inside or around the confined space, the hazards could be classified in several types [2]:

- Hazardous atmospheres: the atmospheric hazard in confined space rise due to: emission of toxic gases; contamination from the nearby environment; flammable or explosive gas, dust, or vapour; previous content of the space

- Unsafe oxygen level: The oxygen-deficient or the oxygen-enrich is a dangerous environment for the worker, the range of oxygen in air should be between 19.5% and 23.5%. An insufficient oxygen concentration can cause symptoms such as tiredness and elevated pulse rate, the person affected may have difficulty in escaping and may be in danger of asphyxiation. Enrichment in oxygen may cause fire or explosion.
- Engulfment: Some stored materials can form bridge or crust in the confined space, which will collapsed when the worker walk on it, so the worker will be immersed by the material.
- Other hazards: biological, mechanical, electrical or environment hazards.

Therefore it is always recommended to do the work from outside the confined space to avoid the risk of working in such hazard area. Otherwise we should control this risk by isolating the contamination, cleaning and purging the confined space, testing the atmosphere for oxygen level and toxic gases, ventilating, and selecting appropriate protective and safety equipment [3].

Silos are the most popular sort of confined spaces, the silo can store a wide range of materials starts from the foodstuffs such as grains, raw materials such as ores and not end with very expensive manufactured items such as chemical compounds and medicines. Three types of silos are used today: the bag, the bunker, and the tower silo. The last is the most used which can vary in capacity from a dozen of kilos to several thousand tonnes, and from few centimetres to tens of meters in height. Woods or bricks were the essential materials for building tower silos, where they have the characteristics of isolation and moisture absorption. But nowadays steel, polymer and concrete are the most common materials for building. Like any structure, a silo must be properly maintained to get the greatest possible service life out of it. Maintenance work could be divided to three substantial job: inspection, cleaning, and repairing. The owner should carefully inspect the internal and external surfaces, looking for any sign of corrosion, cracking, erosion, or deterioration. Before repairing the surface, a cleaning job should be done, the repair work varies from coating or painting surface till replacing the deteriorated area. The internal maintenance is done through inspection holes which are placed in not less than two positions at the top and bottom of the silo, the size of these holes is usually small but enough to allow the worker to enter the space. Cleaning is an essential process to extend the lifetime of the confined space. The stored materials and their residues have a bad effect either by eroding the structure of the confined space, or by contaminate the new and fresh materials. Two type of cleaning can be distinguished for the confined spaces:

- Volume cleaning: enclose to several works such as removing the blockage of materials, sucking the sludge, or any other process guarantee the continuous flow of the stored materials and using the entire space.
- Surface cleaning: concerns with removing buildup material, contamination and infection from the surface, and guarantee the hygienic for it.

3. Cleaning techniques for confined space

Cleaning technique involves strategies used in confined space to increase the efficiency or to prevent or reduce the risk of transmission of contamination from old to new materials. The methods for cleaning large interior surfaces can be classified to wet cleaning, dry cleaning, mechanical cleaning and chemical cleaning.

3.1. The wet cleaning

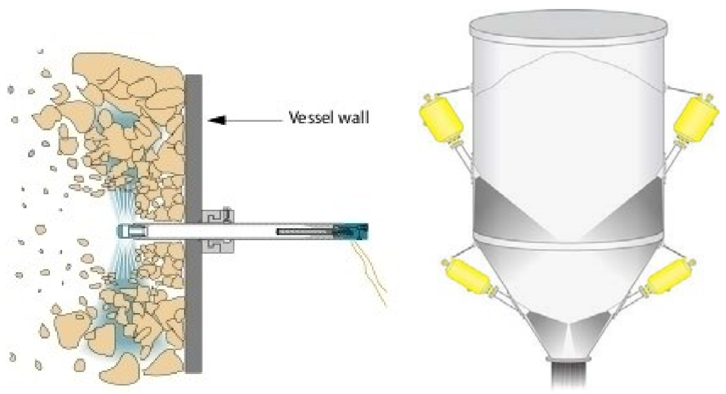
Figure 1: Water-blasting technique, a worker in confined space using a high pressure gun to clean a mud tank on an oil rig support (left), Tank cleaning by lowering a water blasting nozzle inside the tank (right)

In this technology water or any other liquid solvent is used to clean the surfaces in the confined spaces, the most popular technique is the water blasting. **Water blasting**: is a process where a pressurised water propelled at high speed is projected on a surface through a specially designed nozzle. The water blasting is used in applications ranging from removing build up materials, residues, paint, rust to concrete demolition. The water pressure and the speed of cleaning process - all of which can be tuned - control the quality of treatment. This method is used as a final step in surface preparation. Its main limitations are the collection and disposal of waste-water, and the humidity. The debris of the process must be removed immediately to prevent them from solidifying, and the surface remains humid relatively long time after cleaning. This technology has several advantages, it is considered as green technology no dust and limited noise level, no mechanical vibration enforces on the structure, and it is a fast technology.

3.2. The dry cleaning

In dry cleaning there are several technologies to clean the confined space, release pressurized gas, acoustic cleaner, abrasive blasting, pressurizes air jet and mechanical cleaning. **Released Pressurized gas**: this technic is mostly used to dislodge the blocked material, the most common technics are:

- Cardox[4]: CARDOX tubes (figure 2(a)) are filled with liquid carbon dioxide, applying a small electrical charge energizes the CARDOX tube and the liquid carbon dioxide converts to a gas. A discharge nozzle releases the expanding CO_2 and creates a powerful pushing force reaching pressure up to 3000 bar, a single blast can dislodge tons of blockage.
- Air cannons [5]: An air blaster or air cannon is a bulk material removing device which consists of two main parts: a pressure vessel to store pressurised air and a triggering mechanism to release in high speed the compressed air A set of air cannons are permanently installed on silos, bins and hoppers walls (figure 2(b)). They are used for all powdery form of materials to prevent clinging, bridging, rat-holing, or arching and allow maximum storage capacity.



a. Cardox tube [4] b. Air cannon [5]

Figure 2: Released pressurised gas technic,

coustic cleaner [6]: Acoustic cleaning is regularly used to clean the build-up of dry materials and particulates, and for ensuring maximum continuous flow of stored materials in silos. The acoustic cleaning depends on resonance phenomena for loosening adhesions between particles of the stored material itself and the material particles and the container surface. The acoustic cleaner consists of a wave generator which generates a powerful base sound wave and a bell section that transmits the base sound wave into selected fundamental frequencies between 60 - 420Hz. The acoustic cleaner is activated by standard compressed air from the facility for a few seconds at periodical intervals.

Abrasive Blasting: In this cleaning operation, a stream of abrasive material is directed under high pressure and with high velocity to remove surface contaminants and prepare the surface for further treatments. There are two main types of abrasive materials: non-metallic and metallic. Materials such as silicon carbide, sponge, glass beads, sodium bicarbonate (baking soda), plastic blasting media, sand, walnut shells and corn cob are included in non-metallic abrasive materials. Non-metallic abrasive is used for delicate operations such as cleaning the surfaces from stains or mildew, or cleaning the moving parts of machinery from oil or grease. While the metallic abrasive materials include steel shot and grit, zinc cut wire, nickel slag, copper slag, or carbon cut wire. Metallic abrasive is used for cleaning metal surfaces and hard surfaces such as concrete and stone, it is also used to roughen a smooth surface.

- Dry Ice blasting: Dry ice pellets is a solid form of carbon dioxide Dry ice blasting is an effective cleaning process in the food industry to decontaminate equipments surfaces of micro-organisms that are not detectable using classic microbiological methods. Cleaning with carbon dioxide ice is costly and slow process, therefore it is not used a lot in silo cleaning. Advantages are that it does not bring any rest products, it is adapted to environmental demand, merciful against surfaces.
- Shotblating: This abrasive method is used on both metal and concrete surfaces for cleaning and preparing the surface for further processing such as coating, painting, welding. The final result of cleaned surface depends on the physical properties of the abrasive particles (mass, shape, size, hardness), the blast velocity, and coverage and density of the strokes. Two technologies are used:

wheelblasting and airblasting. Wheelblasting is considered environmentally friendly method, because no toxic substances are used, and no waste remain. While in airblasting, the main disadvantage is the waste and the dust which are generated in the working environment.

Figure 3: Silo diver using high pressure air jets

High-pressure air jets: The process uses compressed air and it is commonly used in large food silo, where it is not recommended to use the wet cleaning. The nozzle of the air gun, which directs the compressed air onto the surface, determines the thrust force that is responsible for blowing the buildup materials. Pressurized air is applied to remove different types of build ups materials such as flour, sugar, grain, coal, and fly ash. A regular cleaning process for the container or the silo reduce contamination and guarantee maximum flow of the stored materials. The air source in the facility (6-10 bar) is usually enough for the most cleaning requirements. Some difficult cleaning process need more powerful thrust force, thus, a mobile compressor for providing air at high pressure is required. The most common method for doing the cleaning process is to lower a worker inside the container (figure 3) who applies the pressurized air to clean the container interior surface. The worker should wear personal protection equipment to protect his body. In some implements, the cleaning air jet nozzle is inserted into the container through existing small hole only fit for the cleaning tools. The operation is then remotely controlled from the outside of the container. This technology is safe and totally dry but its main drawback is the intensive dust which is generated in the silo.

3.3. Mechanical cleaning

Mechanical cleaning operations produce the least amount of dangerous waste as no other materials are added to the operation. A wide range of cleaning and surface preparation options are offered by mechanical cleaning processes through using manual or automated tools:

- Brushing: different types of brushes (wire or plastic brushes) are used to clean surfaces from dirt, grease, grime, or build-up materials. Brushed surfaces are prepared for further process such as welding, painting, or preparing.
- Grinding: Two types of grinding can be notified: the aggressive grinding, by using a rotating abrasive stone or disc, cleans the most difficult and hardest build up materials from the surface. the polishing (soft grinding), by using fabric or fibre cloth with polishing cream, clean the surface from dirt, grease, corrosion, tarnish, etc.

- Vibrators: used to dislodge the bulk material, and they are easy to fit into confined space, but can cause structural damage.
- Impact tools: manual devices such as bush hammers, scablers and needle guns are effectively used to remove contamination of surface (figure 4). Automated impact tools use the hydraulic or pneumatic power to activate the cleaning tool, and the command will be from outside the confined space. For example, in the patent apparatus for silo clean out [7] the device cleans the remains materials in the confined space by impacting them, and the apparatus is hung up at the top and driven by a drum.

Figure 4: Worker cleaning inside silo using impacting tool

3.4. Chemical cleaning

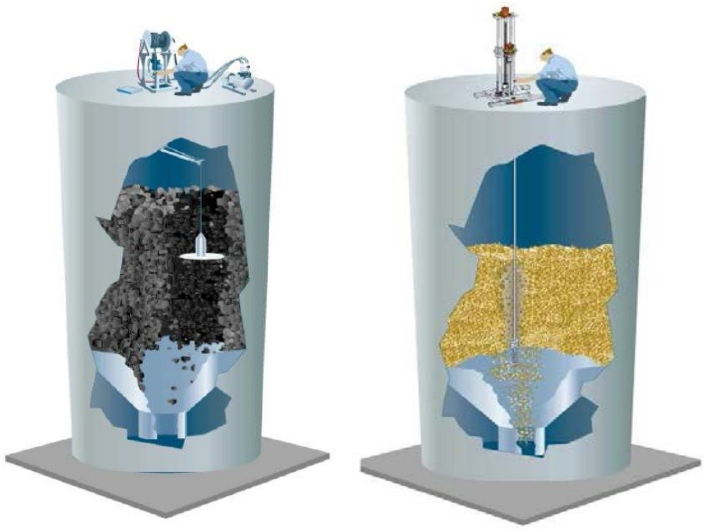
Chemical cleaning process is mostly used to clean unwanted residues and organics contaminants from equipments surfaces, pipelines, vessels and kettles. Several factors determine the choice of chemical cleaning process: nature of the contamination, oxidation type to be removed, cleanness degree, environmental restraints, and the cost, where a variety of chemicals can be used. Pickling is considered the most common chemical cleaning process used to remove oxides and iron contamination from metallic surface. Pickling must be followed by complete rinsing with clean tap water, and the waste water which is acidic and contaminated with dissolved heavy metals(iron, chromium, nickel) must therefore collected and neutralised. Generally, the cleaning chemical method is an easy cleaning process with very good output of cleanness, whilst it is main drawback is the residues.

After this overview of the used cleaning technologies, choosing one of these technologies depends on three aspects, which should be well defined, the surface type of the confined space, the type of materials which are stored, and what is the purpose of cleaning.

4. Enabling robot and mechanism

The basic element in controlling the risk in the confined space is to do the work without entering the space, therefore there are many mechanisms and robots which are invented to do the worker job. In the following we will present some of these mechanisms:

4.1. Suspended Mechanisms



a. whip mechanism b. drill mechanism

Figure 5: suspended mechanism

The suspended cleaning mechanisms are considered best solution to bear the high altitude of silo. In this mechanism the cleaning apparatus is suspended inside the confined space with ropes [8] or beams [9] and all the control command is done from outside the confined space. There are several patents for apparatuses for either cleaning or removing the buildup materials of the surface of confined spaces. Different cleaning technologies are used in these apparatus. Pressurised air jet to clean the surface is used in patents [10, 11]. Acoustic cleaning technic is adopted in [12]. In [13, 14] wet cleaning technic is used. Patents [15, 16] use mechanical cleaning techniques. Most of these apparatus are easy to control they need a team of one or two worker to work with them, those mechanism which are used to remove blockage are very effective. While the main drawback of the apparatus which are used for surface cleaning of large silo is the inaccuracy in cleaning cause on the one hand there is no feedback about the cleaning quality of the surface and on the other hand there is no mechanism to stabilise the mechanism during the vertical movement and the cleaning process. **Hydraulic or Pneumatic Whip:** This mechanism is widely used by cleaning companies in the industrial field (Figure 5(a)). It has a great effect in removing rat-hole blockage, it is easily attached to the manhole at the top of silo. It can be manoeuvred by one operator who manipulates the cleaning head by simple controls from outside the silo, the telescopic boom extends into the silo guiding the hose and holding the whip head, the rotating flexible whips attached to the cleaning head has a cutting action on the accumulated bulk material makes it to fall down and without damaging silo walls. By moving up and down or rotating the boom, the whip could clean the hall space, the whip can clean a silo up to 60 m in height and 18m in diameter. **Hydraulic or Pneumatic Drill:** this mechanism works in conjunction with the Whip mechanism, and also is used for removing bridge blockage (Figure 5(b)). This mechanism is easily attached to the manhole at the top of the silo or fixed on the ground and the auger enter from an inspection hall in the bottom of silo.

Silo-RoboFox [17]: is a mobile usable cleaning robot for feedstuff silos. RoboFox drives up and down at a vertical leadership bar made of aluminium, which is firmly stuck centrically in the silo, a cable winch with a geared motor is used to adjust the height of the robot. A rotation to the robot around its own axis in addition to the movement of the cleaning tools ensure reaching every spot in the silo. It can be adjusted to different silo diameters (Figure 7). A cleaning programme is made by a first one soft course with hot water and cleaning agent. The second operation comprises the main cleaning work with water applied at high pressure (till 170 bar; 2,500 l of water). In a third operation the silo can be disinfected by adding disinfectant agents. The drying of the food silo forms the completion of the cleaning work with hot air. RoboFox is used in food silo corn or component containers which are or were not filled with explosive materials. All vertically stationary round containers (silo) with a diameter of minimal 1.8 m and maximal 5 m and for maximum height 9m can be cleaned by RoboFox (figure 6).

Figure 6: RoboFox [17]

4.2. long reach manipulators

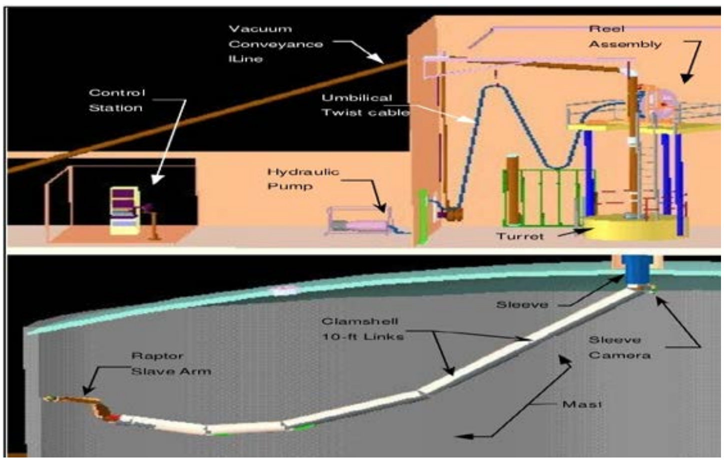
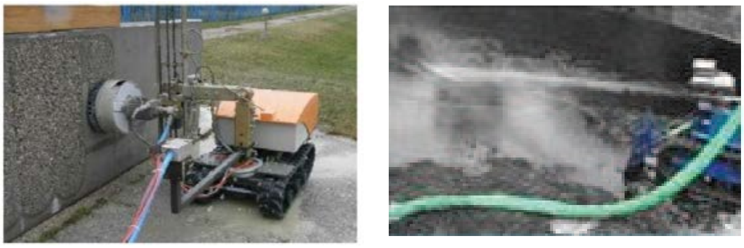


Figure 7: Retrievr system overview [18]

Both rigid and flexible arm manipulator are used, they are mostly used in the nuclear plants to remove the nuclear waste [18, 19, 20], for handling tasks [21, 22] , or for inspection [23, 24, 25, 26]. This solution is used in maximum height up to 10 meters and it needs wide space outside the confined space to install the mechanism, which in most cases is not available. **ReTRIEV**R [18]: REvolving Turret Reeled cable Incremental link Extending Vacuuming Robot is a long reach Robot for Tank or silo waste retrieval, which became a patent for the same inventors Glass and his colleagues [27]. The ReTRIEVR robotic system consists of six link segments (the total length is 18m) and a a six degree-of-freedom arm robot fixed on the end mast. (Figure 7). The segments are joined with active articulation driven by hydraulic actuators. The arm can hold and direct a vacuuming nozzle, or any other cleaning tools that may be required to assist in waste retrieval.

4.3 Robots

Using robotic systems grows up rapidly in the last decades especially in dangerous and hazardous environment, so we can find robot in many industrial fields as: construction and civil infrastructure [28, 29], petrochemical plants [30, 31], nuclear and power plants [32, 33], shipbuilding [34, 35]. The major tasks for these robots are inspection and testing [36, 37], maintenance [38, 39] and cleaning [40, 41, 42, 43].



a. Robot [28] b. Robot [30]

Figure 8: Mobile robot

Mobile robot: Implementing a mobile robot with suitable tools in confined spaces is widely used in the market as a convenient solution for doing the risky tasks. In [28] a modular design of a lightweight mobile robot for hydro demolition of concrete surface and cleaning metal surface is presented. The robot is composed of a tracked carriage and a robot arm with various cleaning tools. Modularity and smaller robot weight allows easy transportation, operation in ordinary construction conditions and manoeuvring in very confined spaces (fig. 8a). While, in [30], an oil storage tank sludge cleaning robot system (figure 8b) is provided with bucket to shovel the sludge and with high pressurized water jet nozzle for cleaning the waste water is collected with suction hose fixed on the robot. The cleaning process is totally monitored through camera fixed on the top of the robot. The system shows high efficiency and high safety and environmentally friendly when it was tested in oil tank. The main advantages of mobile robot are flexibility of mounting different type of cleaning tools and high payload. While the main drawback of using mobile robot in confined space is that it is only used for horizontal surface or small elevation of vertical surfaces.

Climbing robots: The interest about climbing vertical surfaces is becoming increasingly relevant every time the job is classified as dangerous, with possible falls-out on the operator health or safety. Several surveys have presented climbing robots: locomotion, adhesion and application [44, 45, 46]. The major two aspects in designing climbing robots are their locomotion and adhesion. The environment and the given task are the main factors that determine the optimum kind of locomotion principle. In general, four types of locomotion can be distinguished:

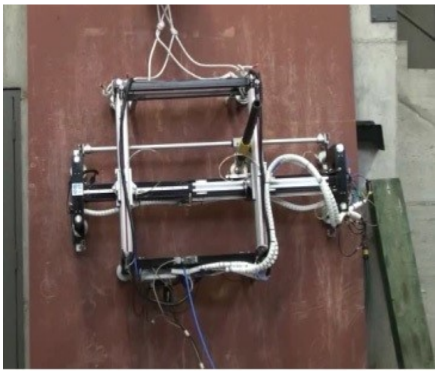
- Legged locomotion [51, 52, 53]: using arms and legs for locomotion gives the robot a great flexibility to avoid obstacles in the environment. The robot could have two up to eight and more legs, more limbs are adopted more safety and high payload capacity is achieved. These advantages will complicate the control system, raise the size and the weight of the robot, and decrease the speed of locomotion. Each foot is equipped with adhesive components such as suction cups, grasping grippers, or magnetic devices, which enable strong and stable adhesion to the surface. The REST1 climbing robot [47] (figure10 (a)) has six reptile-type legs, it has been designed to perform welding and maintenance tasks in industrial environments. Robug II [54] with its four articulated limbs had the mechanical capability to handle wide variety of the terrain.
- Chain and wheels driven locomotion [38, 55, 56, 57, 58]: The big advantage of wheeled or tracked locomotion is the fast and continuous movement and the simpler mechanical structure and control elements. Alicia [48] (figure 9(b)) is a robot designed to search for potential damages or problems on vertical walls such as oil tanks or dams. Using two driving wheels, suction cups, and a vacuum generator keep the operation of the system independent of the surface material. SIRUS [59] uses a magnetic tracks to move over ferromagnetic surfaces to perform nondestructive detection to the external surface of large oil ship hulls and floating production storage offloading.

a. REST 1 [47] b. Alicia [48]

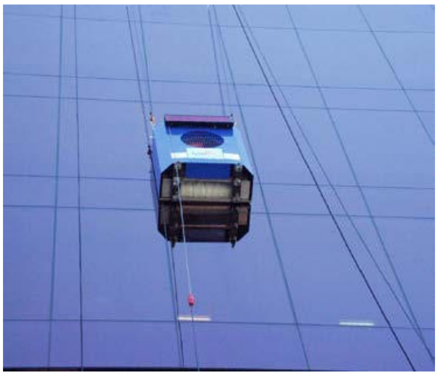
Figure 9: Legged and wheels driven locomotion

- Sliding frame locomotion [60, 34]: These systems provide a simple mechanical structure via two frames which can be moved in a linear or rotational way against each other. In general, each frame is equipped with a set of attach points like suction cups or magnets and keeps the robot at the wall while the second frame is lifted and moved in the desired direction. This allows easy control of robot motion in combination with safe adhesion since the system can test its foot points before lifting the second frame. The drawbacks of this principle are again a low speed compared to wheeled or tracked vehicles, a discontinuous movement due to the stick-move-stick-move cycle, a comparably large size, and the difficulty in crossing cracks and obstacles. Reference [61] is a wall-climbing robot designed for inspection of cylindrical tanks in nuclear power plants, which uses suction force for adhesion. In [49] an unsupervised robot developed for grit blasting ship hulls in shipyards is presented, the robot uses magnetic force for adhesion (figure10(a)).

- Rails and cable driven locomotion: In rails system [62, 63, 64], the locomotion of the robot is determined by the location of the rails. While in the cable system [65, 66, 67, 50] there is no driving mechanism implemented in the robot, but it can move by depending on its weight (gravity force) and on the lifting force of the trolley crane which should be installed on the roof of a structure. The main advantage of these motion principles is that the system is secured and cannot drop off. Tito (Figure10 (b)) is a cleaning robot for building facade which uses two cables to move up and down and it keeps the adhesion to the surface by using propulsion force. The cleaning robot in [40] uses the rails in the building structure to move all over the facade.



a. Grit-Blasting Robot [49]



b. TITO [50]

Figure 10: Sliding frame and rail locomotion

When walls need to be cleaned, the major problem to solve is how to make a reliable sticking of the cleaning device to the vertical surface. The adhesion force for climbing robots can be classified into five categories: Suction force [71], magnetic force [59, 37, 72], mechanical force [73, 74], electrostatic force [75, 76], and biomimetic force [77, 78]. The last two adhesion forces still need more improvement to be able to bear big payload. In sever work environment as confined space the suction, magnetic and mechanical adhesion are used, for being that they have strong adhesion and support large payload.

- Suction force: using the negative pressure adhesion is the most used adhesion method. Three different types can be distinguished: passive suction cups [79, 64], active suction chambers [80, 81] and thrust system [82, 83]. The suction force enables strong adhesion to the surfaces regardless of materials such as glass, metal, and cement. The major disadvantage is that any gap in the seal can loose the adhesion, using several suction cups can overcome this problem. Hence, this type of adhesion is usually used in relatively smooth, nonporous and non-cracked surfaces. Spiderjet 3000 [68] from Hammelmann

Maschinenfabrik GmbH, is surface preparation unit using ultra high pressure water (up to 3000 bar) for cleaning vertical, inclined and horizontal surfaces. Spiderjet 3000 typical applications are ship hull (Fig.11(a)), oil and gas storage tank, and concrete cleaning and surface preparation. CROMSCI [81] is a non-destructive inspection of large concrete walls. It uses seven controllable vacuum chambers and a holonomic drive to cling and move on vertical concrete surfaces.

- Magnetic force: using permanent magnet or electromagnetic actuator can produce a high adhesion force that can bear large payload [84, 59, 37, 31]. The major disadvantage is that it is only can be applied on ferromagnetic surfaces. A maintenance robot for boiler water-cooling tubes [69] (figure 11(b)) has multi-task operating devices consists of ash cleaning, slag purging, thickness measurement and symbol marking. The movement carries through double track and the adhesion is achieved by permanent magnetic blocks fixed on the tracks and designed to fit the shape of the tubes. A large payload capability and passing obstacles are the main features of a wheeled climbing robot with structure magnetic adhesion unit [84]. It is used in welding and inspecting some large equipment.
- Mechanical force: The adhesion is based on claws, spins, or gripping equipment [63, 74, 85]. The robot uses the roughness of the surface to have good attraction points for the spines and uses protrude elements or structure for gripping them. The main advantage lies in travelling along complex environment and in its safety. On the other hand, such systems are not very fast and are of limited manoeuvrability. RRX [70, 86] is a self-travelling robotic system for autonomous abrasive blast cleaning in double-hulled structures of ships. The robot moves inside the ship double hull by gripping longitudinal stiffener. (Fig11(c)).

a. Spiderjet 3000 [68] b. Robot in [69] c. RRX [70]

Figure 11: Different adhesion forces for climbing robots

5. Discussion of design aspects for a cleaning robot for large food silo

A very interesting field of enabling robot for cleaning surface is cleaning tasks of large food silo. A typical food silo has a cylindrical shape with a $20-30$ m height and $4-8$ m diameter, with cement surface. There is at least one circular (diameter 80 cm) or rectangular (80×80 cm) inspections hole placed on the silo roof, usually not placed at the central vertical axis of the silo. So far, cleaning of these vertical structures are made by hand by lowering workers called “silo-divers” through the inspection holes. The silodiver sits on a special suspended on a rope chair and rotates a long-armed air jet around the silo wall. To develop a robot which is able to substitute a trained silo-cleaning worker in operating inside the food silo, must fulfil the following design requirements.

- The robot's form should be compact/foldable to be able to enter the silo through the small manhole;
- The robot must be able to move inside the silo to scan the entire height from top to bottom, letting the cleaning tools reach every point of the interior surface;
- The robot should hold the position during the cleaning process, the robot should bear the reaction force of the cleaning process;
- Possibility to carry the respective cleaning tools and supporting equipment;
- Perception of the interior silo environment, more specifically its surface for quality assessment of the cleaning process.

Table 1 sums up the combinations of cleaning techniques and type of cleaning mechanisms that are useful in cleaning large food silo. One can state, that the suspended mechanism needs a very complicate command system to clean the entire large surface. The long reach manipulator is usually not applied to handle tasks in distance more than 15m. The main constraint in applying climbing robot on cement and rough surface without protrusions is how to keep the robot sticking to the surface while cleaning it. One can sum up, that for cleaning large food silo, a cleaning robot should be able to bear several challenges: the roughness of interior surface, the movability in large space, the safety and reliability of the attachment to the interior surface, and the efficiency of cleaning.

Table 1: Applicability of the different cleaning technics and mechanisms for cleaning tasks on large food silo.

	High pressure air jet	Mechanical cleaning	Abrasive blasting	Wet Cleaning	Chemical cleaning	Acoustic Cleaning	Released pressurised gas
Suspended mechanism	Effective for small and specific areas difficulty in scanning the whole surface			Not recommended for cleaning interior surfaces due to the moisture	Not used for surface cleaning of large food silo	Not effective in surface cleaning	Not effective in surface cleaning
Long reach manipulator	Effective Silo height < 15m						
Climbing robot	Effective cleaning but Difficulty in achieving adhesion force on cement rough surface						

We propose the concept of silo cleaning robot (SIRO) [87] shown on Fig. 12 that appears to meet all these requirements. SIRO consists of two identical platforms, a support unit and a cleaning mechanism. The foldable form of the robot enables it to enter from the small manhole. Due to extremely bad conditions for adhesion, the only feasible way is to suspend the robot bearing the cleaning tools equidistantly to the wall. The vertical position of the robot is changed by varying the length of the suspension steel cables. The rotation movement of the cleaning tool around the silo axis in addition to the vertical movement of the robot permits the robot to clean the entire surface. A stabilization of the robot is strongly needed during the cleaning process to avoid physical interaction between the tools and the wall that can damage of the tools. It is achievable by using minimum three supporting arms which contact the wall, (Figure 12(b)). In addition, these arms climb up/down by crawling type of movement.

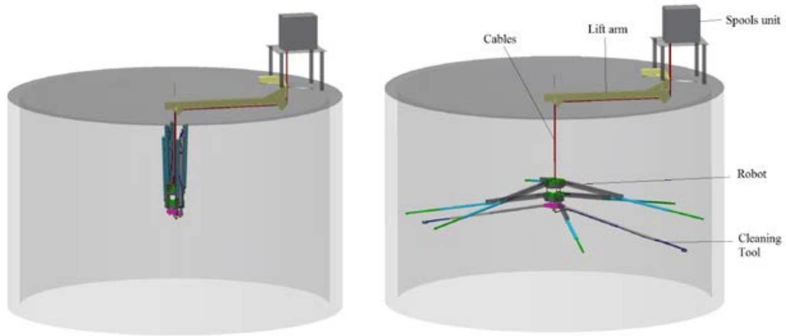


Figure 12: SIRO inside the silo

6. conclusion

In this paper, a survey of cleaning technologies inside confined space with high potential that have been applied for large confined space such as silos and large tanks has been presented.

The two major cleaning techniques, the wet and the dry cleaning, are discussed. Where the cleaning technology depends on the type of buildup materials that stored inside the space, and the surface material type of confined space. Robot and mechanism solutions, which are used in cleaning and inspection of large confined space, are examined. Most robots are used for inspection and maintenance tasks where the payload is too small. Further, different principles for robot locomotion as well as for attraction to the vertical structures are presented. Most existing cleaning robots are used in small and metal confined space.

As a conclusion it can be said, that the field of cleaning confined spaces and interior surfaces formulates a number of specific requirements, which are not met by the existing commercial products. So far, still lowering a worker inside the space is the most used technology and only some special solutions in terms of robotic prototypes exist which are limited to a specific setup or certain environments. Therefore, further research in the future to design a specialized robot for the cleaning and sanitation in large confined space has to be achieved.

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