International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:6, No:8, 2012

Novel Mobile Climbing Robot Agent for Offshore Platforms

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***Abstract*—To improve HSE standards, oil and gas industries are interested in using remotely controlled and autonomous robots instead of human workers on offshore platforms. In addition to earlier reason this strategy would increase potential revenue, efficient usage of work experts and even would allow operations in more remote areas. This article is the presentation of a custom climbing robot, called Walloid, designed for offshore platform topside automation. This 4 arms climbing robot with grippers is an ongoing project at University of Oslo.**

***Keywords*—Climbing Robots, Mobile Robots, Offshore Robotics, Offshore Platforms, Automation, Inspection, Monitoring.**

I. Introduction

THERE is a fascinating supply chain system transferring experts and supplies back and forth to offshore platforms by helicopters or marine vessels. Any interruption in this magnificent chain supply system would result in financial loss and in some worst cases, life threatening situations. However keeping such system going smoothly requires a very efficient management and huge amount of resources. On the other hand, oil and gas platforms are among harshest and most dangerous working environments, but one of the best paid, as experts working in such environments are usually subject to irregular and long working shifts and life threatening situations [2], [13], [17], [18]. Despite functioning, current situation imposes difficulties both for employers and employees. Employers suffer from high chance of unscheduled shutdowns, which are the most costly ones, due to the issues caused by human operators, interruption in the supply chain system and last but not least very harsh environment imposed by the nature [5], [6]. In addition early retirements, injuries and epidemic diseases are other issues which could be considered [13].On the other side, the employees suffer from HSE issues, difficult long shifts (12 hours) and dangerous working environments and longing home [6].

Such issues could turn into critical problems as the time goes by. Future platforms are about to be in areas which are even more remote with harsher environments (e.g. Shtokman, Sakhalin and Arctic) [5]. Such platforms were stamped non-economical before, but today thanks to ever rising oil price, their status are being reconsidered. To be able to operate in these areas with least transportation routes (not accessible all year long) and as little crew as possible, the industry requires new technologies and infrastructures. E.g. Shtokman field far in Bernt Sea could hardly be accessed in half a year [5].

At the same time reports also warn about potential extra revenue or loss of fortune depending on implementation of remote and integrated operation in the area of oil and gas industry [16]. Such reports are taken seriously by oil and gas industry and as the results several projects have been started to bring integrated operation to offshore platforms. Projects such as TAIL IO for Statoil, Smart Field (Shell), Field of future (British Petroleum), i-field (Chevron) [8], [9], [21]. All of these projects have a similar goal and it is to migrate the human workforce to onshore facilities and allow the process to be remotely controlled or totally automated. It is interesting to mention that 4 out of 6 sub-projects of TAIL IO project, implemented by StatoilHydro and ABB, were based on Robotics, automation and IT infrastructures allowing remote operation [8], [9]. The number of onboard crew in such solutions would be minimized to the minimum number, but kept at a low level for safety reasons [14], [15]. Due to all earlier mention points, the market has high potential motivations to invest in the area of topside automation of oil and gas platforms. For better overview one could list the reason in the following list.

1) Better Health, Safety and Environment (HSE)
2) Cost and production efficiency of automation / integrated operation
3) Future platforms could not be built without newer technologies

Automation by remote and intelligent agents is the key concept in such approaches, as it could replace human workers onboard, allowing the process to be either automated, remotely controlled, or by a middle solution. This is an area of application that oil and gas industry has been invested for a long time, but only regarding under water operation. Thanks to such investments Remotely Operated underwater Vehicle (ROV) technology today is considered a stable technology, helping both in operation time and in case of crisis [5], [18], [19]. On the other hand the topside was almost untouched during all these years until recently when the changes made topside automation a very attractive topic for oil and gas industry [5]. Such changes could be mentioned as following.

1) Future platforms and discoveries in very remote areas
2) Ever rising oil price which made previously non economic project profitable
3) Reports encouraging the industry to implement integrated operation and warn about consequences of not

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doing so.
4) Better HSE level (hidden coasts, injuries, early retirments, reputation, national issues, etc)
5) Cost efficient automation and potential revenue which covers automation expenses

II. Background

The offshore platforms could be divided into two main parts, topside and subsea. Robotics automation is already serving oil and gas industry in some areas of applications. E.g. pipe inspection, submersibles and drilling [2], [11] which are all impossible areas for human workers to operate at. However not much automation was introduced to topside as the same needs were never felt [5], [6] Following subsections discuss the opportunies and challenges around the new attractive area of interest, topside automation.

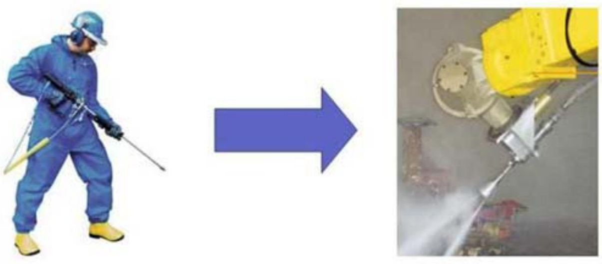
A. Opportunities in Automation of Offshore Platforms

Earlier literature in offshore automation field show a wide variation of opportunities for robotics automation (mobile and fixed) in offshore platforms [2], [5], [6], [8]. Same studies also underline that studying the everyday work-plan of human operators on platforms show that most of their time is used on repetitive tasks. Such tasks could be mentioned as following [2], [5], [6].

- Walking around platform to reach specific areas
- Transport
- Regular inspection
- Monitoring the ongoing situation
- Maintenance assignments

Such repetitive tasks could be easily taken over by a combination of robots and other smart agents if inter-connected and equipped with proper sensors / tools. It's important to mention that the complexity arises when one moves from inspection robots toward manipulator robots, specially on floating platforms or mobile ones without a fixed origin [2], [7]. Such approaches taken by industry would create better working environment for human workers (onshore office work with higher HSE standards) and could increase the revenue. This results from academia is also backed up with governmental and industrial reports [2], [5], [6], [13], [16].
Automation and remote controlling technologies require very good IT infrastructures to allow the human operators to control / monitor the system from far distance in onshore facilities. TAIL IO, thanks to the fiber cables beneath North sea, has created a unique situation which today one could join extraction of petroleum, while having plans for dinner with friends at home after work [8], [9], [14], [15]. However this is only the start and this new trend of automation on topside requires new robust technologies to be developed [5], [6], [8], [9]. However such development projects for harsh areas of applications such as offshore platforms would not be easy and require attentions on both potential and challenges that these environments contain (see fig. 2). To have a better overview over the area of application, one could divide platforms into following categories [2].

Fig. 1 Washing off salt from machines is a daily task at offshore platforms and a possible future assignment for robots [5]



- Shallow water: Platforms in waters with maximum 200m depth, mostly two jackets (3-5 decks) connected with bridge (fig. 2).
- Deep water: Platforms in waters with beyond 200m depth, with only one jacket with more than 5 decks.
- Floating: Almost like a ship than platform and very flexible in changing locations.
- Unmanned: There are several wells in big fields. These platforms are usually maintained every 2 weeks with a crew of 2 - 4 operators.
- Subsea: Wells and installation which are mounted under the sea. These platforms are fully automated with use of ROV.

Beside subsea wells that are already automated by ROV 's and Autonomous Underwater Vehicles (AUV), all other types of platforms could be the subject of topside automation, specially unmanned platform. After categorizing the areas of application, one could also point out the possible assignments that one automated / remote controlled system could be used for [2], [5], [6].

- Live video feed of environment
- Gauge readings
- Valve and lever position readings
- Monitoring gas level
- Acoustic anomalies
- Surface condition
- Check for intruders
- Gas leakage
- Fire detection and locating
- Transportation

Fig. 2 Left to right: Extreme weather condition on platforms | Shallow platform [2]

- Maintenance (e.g. washing off salt from other machines and robots, see fig. 1)

B. Challenges in Automation of Offshore Platforms

Oil and gas platforms have their own properties, limitations and challenges. Challenges that could very from very severe HSE requirements to extreme weather condition, vibration, salt water, banned radio spectrum in different countries and etc [2], [5], [6], [9], [10]. Generally such challenges could be summarized into following points [5], [6].

- Organizational changes followed by such automations [5], [21]
- High HSE requirements (high redundancy)
- Extreme weather conditions
- Salt Water
- Rust
- Offshore Standards (NORSOK, ISO, DNV SfC 2.4, IEC 60945, MIL-STD-810 [6])
- Vibrations (special cases, floating platforms and marine vessels [7])

III. Climbing Robots

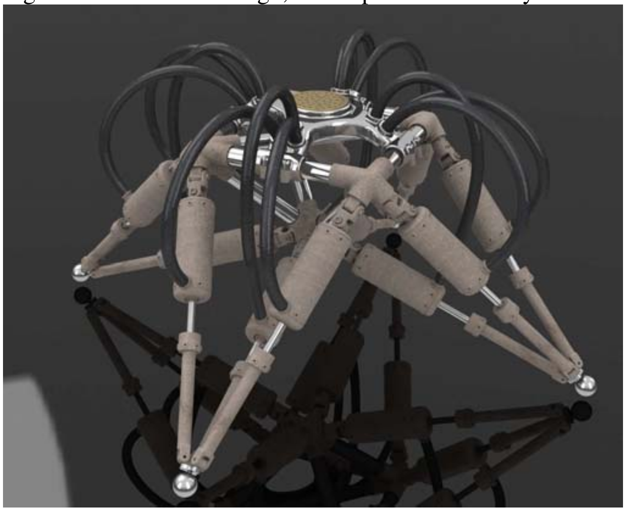
There are several works focusing on climbing robots in general, but very few of them do that regard to the environment in offshore platforms. In recent years the maturity and stability of climbing technologies have resulted in increasing number of climbing robots in industrial applications (both remotely controlled or autonomous) [4], [6]. Such areas of application are cleaning skyscrapers, nuclear facilities and petro-chemical products tanks [6]. These areas regard robustness and stability of the systems among highest requirements.

Based on Locomotive abilities, climbing robots can be divided in three main classes, ”wheeled / tracked locomotion”, ”legged locomotion” and ”arms with gripper’ locomotion” [4]. Usually robots developed with arms and grippers or legged locomotion, fits best in more complex surfaces (e.g. oil and gas platform with various surfaces), while the wheeled/tracked locomotion fits best even terrain like glass, concrete, brick , steel walls [1], [4]. For these locomotion types, different types of adhesion forces could be used to keep the robot from falling off the wall. These adhesive forces could be categorized in following classifications [4], [6].

- Magnetic force (permanent / electrical)
- Negative Pressure / Vacuum
- Grasping
- Pressing to the inner wall
- Van derWals force (inspired by nature, e.g. Gecko)

Moreover it is now time to name some of the general critical requirements in development of any climbing robot. Such requirements could be stability, flexibility (ability to handle a variety of terrains), surface contacts issues, power consumption, force distribution, overheating of motors, and climbing between adjoining surfaces [4], [12]. These requirements plus the additional specifications or local issues for each area of application (e.g. offshore platforms requirements) are challenges that every project would face during development phase.

Fig. 3 Walloid latest design, developed at University of Oslo



IV. Walloid, the offshore climbing robot

Walloid (fig. 3) is a 4 arms quasistatic climbing robot which is an ongoing project at robotics and intelligent system group (ROBIN), department of informatics, University of Oslo. The first rapid prototype of Walloid project was only a simple prismatic joint. Later a second version was made which contained central chassis and one arm, consisting of three prismatic joints (see fig. 4). The prototype at this stage, was ***printed by a 3D printer*** at University of Oslo. At this stage the work continued with testing the early prototypes and finding the issues around the concept.

Today the first complete version of Walloid prototype is built in aluminum and ABS pluss. Today’s prototype is based on the early design with some minor modifications (fig. 5). Although the building process of the whole chassis is finished, the work continues on the type of end effectors and other remaining areas of the project. The Walloid project could be described as a prototype with following features listed below.

Fig. 4 Early prototype of Walloid arm

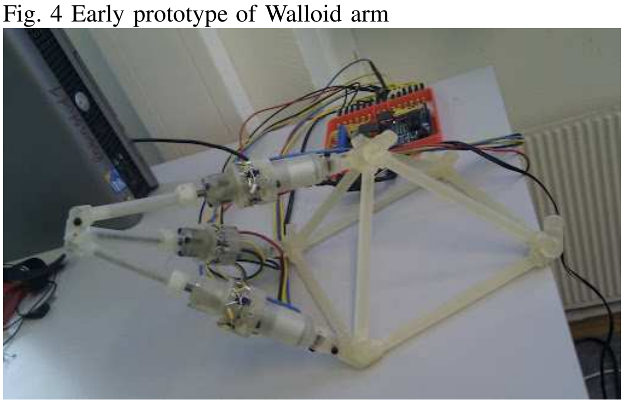
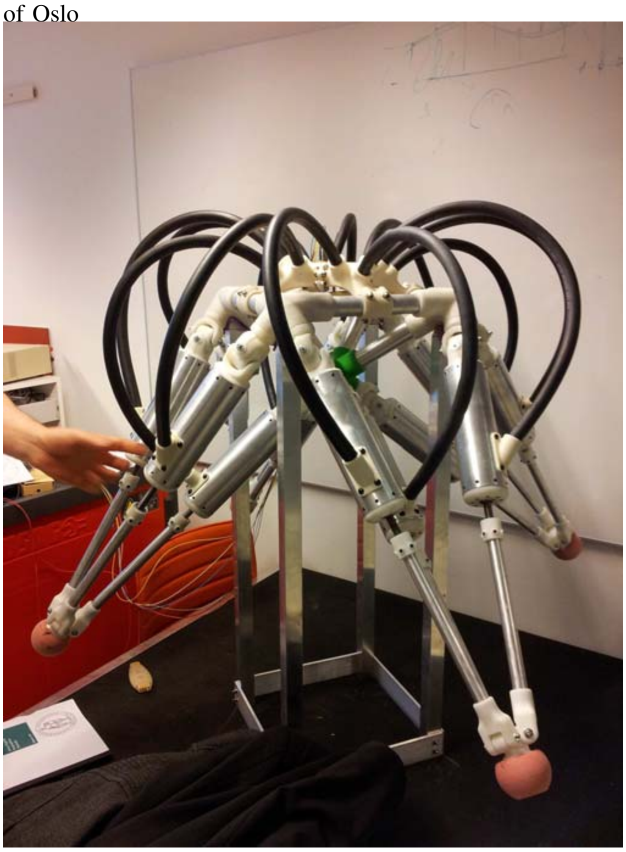


Fig. 5 Walloid latest rapid prototype developed at University of Oslo



- 4 arms and grippers climbing robot (irregular tetrahedron shaped arms)
- 3 prismatic joints per arm
- In-house developed custom encoder solution (light fork sensors and a custom rotary joint
- Very precise movement of prismatic joints (0.25 mm per encoder reading)
- Decentralized hardware design, where each arm is controlled by separate micro-controller

A. Walloid Features

- inspiration from nature
Observing the natural climbing methods (both dynamic and quasistatic), one could see how evolution has evolved toward four arms (or 2 arms and 2 supportive legs) climbing techniques. This is due to the very stable force distribution and balance among the whole body [6]. Based on these findings, Walloid was designed with 4 arms to optimize force distribution among the whole chassis. *Ű Stability*
The 4 arms robot would guarantee the stability of the system, as one has the freedom to choose the gaits in a cautious way to increase stability. The cautious way of climbing simply would be to keep enough number of arms stick to the wall during strides and lifting operations [6].

- Lower power consumption and prevention of motors overheating
Walloid was designed to guarantee homogenous force distribution among the whole chassis. This would also prevent overloading and therefore overheating of electric motors. In addition this design would also help in lowering energy consumption. The legs (supportive back arms in a legged robot) provide a stable resting place (no energy consumption) for a climbing being, the same issue applies to the robot, where the back supportive arms would be able to stabilize the process and also carry the load without energy consumption [6].
- Freedom of choice in adhesive force
As mentioned earlier in *climbing robot* section, a climbing robot could use different adhesion methods to stick to the wall. These forces were categorized in 5 different sources (III). One of the advantages of Walloid project is the freedom of choosing the adhesion force. This means that the whole project was not designed based on one single type of adhesion force and one could always change the force type during development, regarding area of application and different purposes. The ”arms based locomotion feature” could easily allow each kind of earlier mentioned adhesion forces to be implemented in the project and this opens the doors for several opportunities for further developing the project based on ”path free” or ”path dependent” methods. E.g. magnetic force could be a fair choice when it applies to the metal platforms (path-free) which are placed in warmer areas, however same solution could face difficulties facing situations where the surface is covered with a thick layer of ice (North Sea).
- Flexibility
In addition to earlier discussion about benefits of arms locomotion, this locomotion combined with grippers fits best complex and various surfaces such as those in offshore environments [1], [4].

B. Suitable for Offshore

- General Requirements
Walloid features and the way they would satisfy the general requirements of one climbing robot was discussed in IV-A, however some of these requirements are taken more seriously in offshore environments (e.g. stability and redundancy).
- Proofing Issues
Earlier in II-A it was explained how the easy repetitive tasks of human operators in offshore platforms create an exceptional opportunity for mobile agents to take over these tasks. However it was also pointed out that the harsh environment of oil and gas offshore platforms would not even be suitable for machines and electronics boards, that would include robots [2], [5], [6].
Regarding proofing issues due to the destructive effect of salt, humidity and rust on electronics boards (see cables and boards tubing in fig. 3 and 5). However even the robot outer parts would also be in direct exposure of such destructive elements and one needs to pay especial attention to building

materials when manufacturing Walloid as a product for such environments (e.g. stainless steel or even stainless titanium).

- *Stability and Robustness*

In addition to these design features, choice of methods and technologies in Walloid development was done based on requirements in such harsh environments and standards around them. E.g. the high HSE rules by NORSOK standards would require active machinery in North Sea platforms to be highly stable [10].

Accordingly choices of adhesion were decided to be the most stable in terms of both functionality under normal condition and emergency situations (e.g. sudden loss of power). Therefore one could eliminate other choices from the list and end up with only arms and grippers as the right choice for this area of application (see IV-E). Choice of grippers also would add up to the robustness of the system as the grippers would still let the robot to hang to the wall in case of loss of power, while other adhesion forces would eliminate and leave the robot to the natural physic laws (fall and bridge of HSE requirements). Based on all these, arms and grippers with 4 arms, combined with cautious climbing gaits is the right choice to reach high stability and robustness.

- *End effector and bolts design*

The choice of grippers has made the Walloid path dependent. Meaning the robot always needs pre-defined path to be able to climb vertical surfaces (see fig. 7). This might bring up positioning issues, however the design of end effector for the Walloid arms and the bolts were done regarding this with having tolerance in the positioning and therefore increasing the rate of success climbing attempts (see IV-E). This would specially be helpful regarding vibration in floating platforms [7].

- *Flexibility*

Offshore environments are known to be complex and unpredicted [6]. Continuing previous discussion about choice of arms and grippers, one could also reason that combination of such adhesion method would be very suitable for complex surfaces and adds to the flexibility of the system.

- *Elevation between different floors (levels) of platform*

Climbing robots have a big advantage in front of other types of mobile robots in offshore platforms and it is their ability to climb and therefore reaching different floors of one platform. One could also further develop the climbing robots to be water proof and reach under water parts of one platform as well.

- *Robustness issues*

During Walloid project the robustness issues were addressed often and very carefully. This is discussed in V.

C. Walloid compared with other existing agents

To compare Walloid with other mobile robots designed for offshore platforms, one does not have many choices to choose between as this area is very much untouched. One industrial example from Fraunhofer Institute of Manufacturing Engineering and Automation is a mobile robot for Offshore inspection and manipulation [2]. This product has been recently attracted attention of oil and gas companies for topside automation [6].

Fig. 6 Control System Hardware

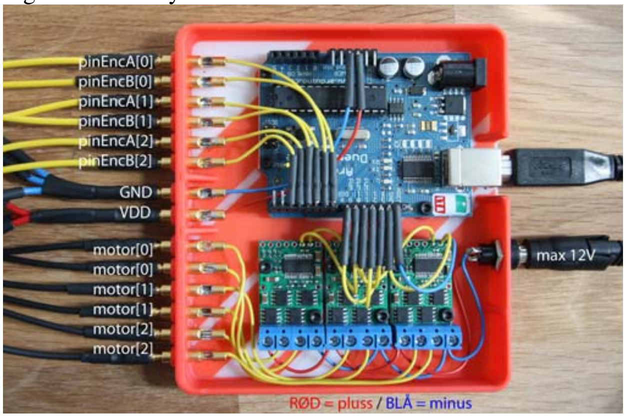


TABLE I Walloid robot arm hardware setup

No.	Name	Manufacturer	Quantity
1	Atmega 328 8bit	AVR	1
2	DC motors, 12 V	Elfa	3
3	Motor drivers	Pololu	3
4	Encoders, in house developed	ROBIN	3

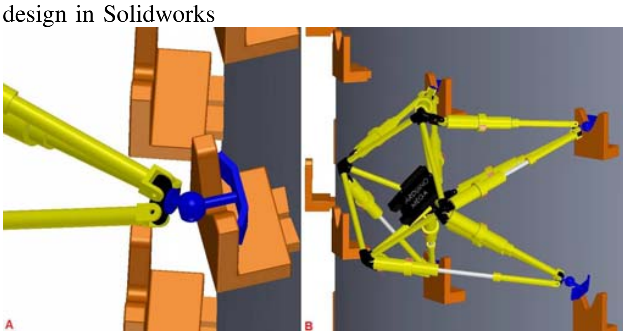
This robot is a wheeled mobile robot with ability to cover big grounds in the same level in one platform and monitor the situation. However as the producer also confesses this robot could not elevate between different levels (floors) and is only suited perfectly for shallow water platforms [2]. Although Fraunhofer prototype could beat Walloid in speed and being path free, but when it applies to a single type of robot being able to cover the whole platform and reach extra dangerous areas, Walloid could show much better performances. Compared to other types of climbing robots, Walloid, as a climbing robot with arms, enjoys the freedom of choosing its adhesion force. This feature could be used to build Walloid in different versions for different approaches and purposes in different industries and areas of application. In addition the irregular tetrahedron shaped arms (also similar to Stewart platform) with 3 very accurate prismatic joints (based on screw shaft) is another advantage that Walloid has over the other robots. This allows the further development for adding tools on the end effector on each arms (e.g. each arm could carry one tool).

D. Irregular Tetrahedron Shaped Arm

Each Walloid arm consists of three prismatic joints, which each of them includes one DC motor, one motor driver and one encoder which all are controlled by one micro-controller (fig. 4). The prismatic joint is based on a moving screw shaft whose turns also interrupt the encoder sensors. Each time the encoder is interrupted the screw shaft would move 0.25 mm (precision). Each joint's electronics are connected to a micro-controller and is controlled from that entity. All in all each micro-controller controls 3 joints which make one irregular tetrahedron shaped arm.

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:6, No:8, 2012

Fig. 7 Final Design assembled with the rest of the Walloid design in Solidworks



E. Grasping End Effector

The process of developing an end effector relies completely on the arm design and the type of adhesion force. As discussed in IV-A and IV-B, the recommended adhesion force for Walloid would have been arms with grippers, regarding prioritizing stability and flexibility of the system.

The final design was assembled with the rest of Walloid design in Solidworks (fig. 7) and simulated. Specifications that were expected from an end effector for a climbing robot designed for offshore application is presented in the list below.

- Preventing the fear for fall in case of power interruption (redundancy)
- Tolerance against limited errors in positioning - Offset angle (redundancy)
- Flexibility

In addition to the end effector, the hangers / bolts (where the robot hangs on) have to be designed in a way that together they would satisfy the specifications. Fig. 7 shows the designed bolts and the corresponding end effector for such gripper solution.

If planned and designed carefully, one could use the gripping feature to naturally satisfy the fall prevention in case of power loss. This could be possible if the hanging feature is only dependent on mechanical shape of the grippers and not electrical motors. Fig. 7 shows how this important point was considered during the design.

On the other hand possible vibrations (especially in floating platforms) and lack of precision in the control system could always lead into errors in positioning of the end effector on the bolt [7]. However, if the bolt and end effector were designed in a way to give some tolerance for error in positioning, less precision would be required. This error tolerance feature adds flexibility, increases the success chance in grasping operation and could save climbing time and prevent extra power usage and last but not least would decrease the need for manual positioning in case of too many errors. Therefore the suggested design in fig. 8 was presented to satisfy almost all the required features.

Beside earlier considerations for adding to flexibility and error tolerance of the gripper, lastly it was decided to equip the gripper with a spherical wrist (see fig. 8) on the top (at the mounting point). This design improvement added extra flexibility to correct errors in positioning during grasping. The spherical wrist would bend according to the mechanical resistance from the surface of the bolt. ItŠs much easier to correct such errors with smarter mechanical designs, rather than having several sensors gathering around the end effector and try to position the motors to reach 100to be able to come back to the zero position of the end effector in case of absence of resistance from other materials (elastic properties of rubber). Such solution is easy to implement and very easy to maintain which are among important issues in industrial prototypes.

F. Walloid Workspace

To calculate the workspace of the robot, the length of each joint is required. This could be calculated through the initial length of the arm (L0) and the amount of added length. The added length would be also accessible by having the minimum length on each encoder reading (shown by l and is equal 0.25 mm for Walloid prismatic joints) multiplied by the number of encoder readings or a counter (n). The equation to calculate the length of one joint is shown in equation that follows:

$$L = L0 + (n * l)$$

L = Current Length of the joint L0 = Initial length of the joint n = Encoder counter l = minimum length added by one encoder counter (0.25 mm)

The experiments during testing the prototypes showed that the encoder counter could vary between 0-217. Having the length of one joint, one could imagine intersection of three imaginary variable spheres around each starting point of the prismatic joint. This would result in two points, which one is unacceptable (inside robot cahssis), allowing calculation the current conjunction of the three joints at each time (similar to GPS concept).

$$\mathbf{R1\hat{2} = (X\text{-}X1)\hat{2} + (Y\text{-}Y1)\hat{2} + (Z\text{-}Z1)\hat{2}}$$
$$\mathbf{R1\hat{2} = (X\text{-}X2)\hat{2} + (Y\text{-}Y2)\hat{2} + (Z\text{-}Z2)\hat{2}}$$
$$\mathbf{R1\hat{2} = (X\text{-}X3)\hat{2} + (Y\text{-}Y3)\hat{2} + (Z\text{-}Z3)\hat{2}}$$

Based on these calculations, the workspace was generated in Matlab. Fig. 9 shows the workspace for the whole robot.

V. Robustness

Robustness or error handling is the ability of the whole system to cope with the errors that occur during the operation. Errors could happen in any embedded systems. Therefore, the error handling should be expanded to monitor them in different processes, in all layers. Thereafter, the system should try to

Fig. 8 Final Design assembled with the rest of the Walloid design in Solidworks

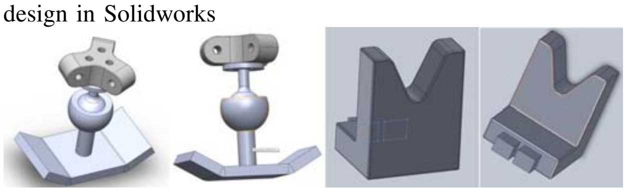
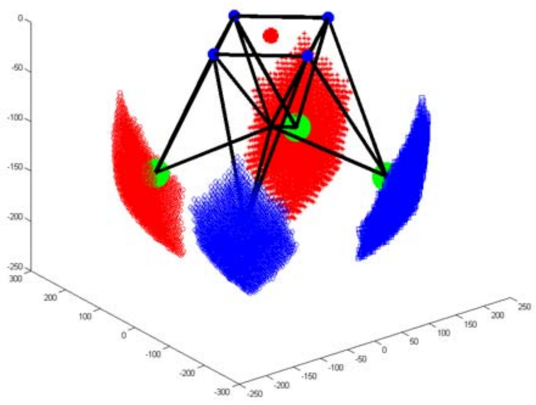


Fig. 9 Robot workspace generated in Matlab



handle the situation and recover from the critical state to the normal state. The issue of recovery is very important, as it is almost impossible to fully stop errors from happening. Having an embedded system in our hardware and software controller level helps us in expanding our error handling system downwards to each part and also allow each controller to announce emergency situation in case of loosing contact with other parts of the system (communication failure). Beside these one should also be aware of following critical situations while developing a robust system for the industry.

- Passive Joint Control (critical)
- Power loss and HSE issues (Critical)
- Self awareness after power loss
- Adjoining Surfaces, current angle of system and vibrations
- Battery charging issues

VI. Conclusion

Walloid is a promising prototype for oil and gas offshore environments. Although it's still an ongoing project and is being perfected through tests and academic reviews, but the development process of the project has made it a promising piece of work for further development and investment by the industry. Current design satisfies several critical requirements of a climbing robot such as stability, flexibility, homogenous force distribution, minimum the power consumption and prevents motors overheating. In addition the combination of this design with choices of methods for Walloid, e.g. proofing, grippers, bolts and robustness issues, allow even more stability, robustness and flexibility needed for industrial applications such as offshore platforms. Regarding control hardware system, the initial design of control hardware system as an embedded design, could be a proper starting point for further development into a complete decentralized distributed control system both in hardware and software level (full scale control system).

Another area of interest for further development of this project would be the climbing gaits which are very important for a robot to be able to climb the vertical terrains efficiently. Topics of climbing gaits is a very critical and could effect earlier mentioned issues such as stability, power consumption, force distribution and overheating of motors. It's also very important to pay special attention to stability and speed issues while working on this topic.

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