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Process Optimisation and Design of an Automation Controller for a Multi-disciplinary Combat Engineering System

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ABSTRACT

The design of an automation controller for a "Electro-Hydro-Mechanical Object Laying System" presented in this paper is multidisciplinary equipment. It consists of Electromechanical, Hydraulic actuators several sensors for process feedback. The conventional object-laying process is a time and labour-intensive manual process. Another way of laying the objects is through mechanical layers, in which most operations are mechanical, require constant human intervention, lack operator safety and don't provide location marking data of laid objects. Commercial-Off-The-Shelf (COTS) method is adopted to develop the apparatus. There are complex mechanisms and processes involved in this apparatus, which are required to be operated/executed in a sequential and parallel manner in real-time. Based on the computational requirement for the Controller, the cPCI bus-based rugged architecture has been adopted with software built on RTOS. Operation synchronization of spatially distributed Electromechanical & Hydraulic actuators is required. Safe handling of the objects is one of the critical requirements. All the activities are automated with minimum human intervention to avoid risk to the crew. The resultant outcome of this process is the time reduction for object readiness by 54 % without compromising safety. We achieved average object marking accuracy up to 30cm in dynamic conditions on the vehicle platform using differential GNSS with multi-constellation and augmentation system support. This paper mainly focuses on electronic controller hardware design for military environments and process optimization to achieve a faster object laying rate.

Keywords: Controller; Combat engineering; Automation; cPCI; Electromechanical; Hydraulic actuators; Sensors

1. INTRODUCTION

The automation of military equipment is a challenging task. It is required to be executed with limited space constraints, extreme environmental conditions and compliance with stringent Military standards[1-6] on the electronics system designer. The System requires continuous efforts for the development of reliable, compact, modular and ruggedised electronic sub-systems with high I/O density & real-time response. It is in the interest of the security of a nation to have such advanced and state-of-the-art equipment in the armed forces[7].

In a war scenario, countries use different defensive and offensive strategies to combat enemy threats[8]. Laying objects is one of the crucial defensive strategies to delay the advancement of the enemy movement in our territory[9]. Main Battle Tanks and other ground-based supporting vehicles are the main components of the modern army that supports the infantry. An object planted beneath the ground restricts the entry of the enemy's heavy vehicles inside the area of domination.

The conventional object-laying process is a risky and labour-intensive activity because of the abundance of explosives. The laying rate is low and requires a large crew for manual processes. In mechanical object layers, the requirement of crew members is less. The risk factor involved was high, as the arming was manual. Also, these processes do not have any provision to precisely mark the location on the map for easy and safe retrieval. The object-laying process can be divided into various operations as shown in Fig. 1. Automation shall help overcome the shortcomings of traditional ways of object-laying.

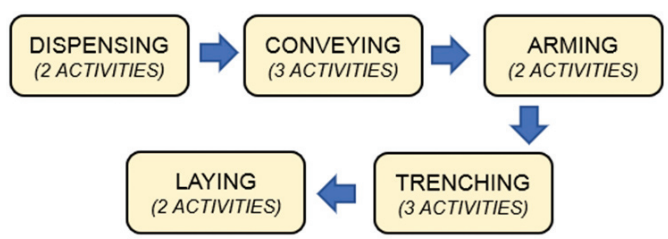

Figure 1. Object laying operations.

This equipment shall have the advantages of improved object-laying rate, precise object location marking, a significant reduction in crew members and a safe object-laying process.

2. ASSUMPTIONS AND SYSTEM CONSTRAINTS

The design presented in this paper is required to meet various Military standards. These standards present a challenge in terms of qualitative and environmental requirements.

This equipment is required to lay and bury objects at a higher rate with variable inter-object spacing in different

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terrains like plains, semi-desert and deserts with limited crew members without compromising safety. The objects are buried inside the ground at a certain depth & camouflaged to avoid visibility to the naked eye. Object location is required to be marked precisely on the digital map.

The controller is designed using COTS modules[10]. The specifications of these modules were finalised based on the field requirements. These modules are expected to meet the stringent functional, environmental and performance requirements over the product life cycle. The object-laying processes were divided into sequential multiple operations during the design phase. These operations were required to be executed using electrical and hydraulic actuators. It was assumed that all these actuators should be able to meet the overall qualitative requirement of object laying rate for a given Mission, considering their response time, torque-speed characteristics, etc.

The equipment should sustain extreme environmental conditions, including protection from water ingress and dust & wide operating temperature range from –20°C to + 65°C. The apparatus should also comply with stringent military EMC standards. The equipment has to achieve all the above parameters on a mobile platform in highly dynamic geographical terrain with transverse and longitudinal slopes.

3. DESIGN PHILOSOPHY & ENGINEERING APPROACH

The apparatus was designed based on a COTS-based hardware approach with centralized control architecture to meet the design challenges and expedite the project development cycle. COTS is an item that is packaged & leased to the customers, readily available in the market[11]. COTS reduce the system development time to a great extent.

The mechanical and hydraulic systems were designed based on the qualitative and operational requirements. All these mechanisms were required to be automated to minimize human intervention. Initially, for the concept design of the electronic control system Requirements Analysis was carried out. The sub-systems were designed considering the interfacing requirements of each sub-system. All the sub-systems were interfaced with each other through an Ethernet link, as described in Fig. 2.

The Main Controller is the heart of the system because the control system is designed based on centralised control architecture (Fig. 2). The Main Controller has been developed based on a Compact PCI (cPCI)[12] bus-based architecture. cPCI architecture is a high-performance bus that follows standard PCI specifications. The cPCI bus supports up to 8 slots for I/O cards, in which each slot can have one carrier card that can accommodate two IP modules. It combines a popular PCI interface with a Eurocard form factor and a high-density IEC pin & socket connector into a rugged package. All the dimensions of the mechanical components are standardized by IEEE, which resulted in several vendors who can supply components that can be replaced[13].

The closed-loop servo motors as electrical actuators were selected based on the system requirement analysis. The main parameters considered were torque, speed and motion profile while selecting these actuators[14]. The torque requirement ranges from 3-150 Nm and speed from 100-3000 RPM. A trapezoidal motion profile was considered for the optimum utilization of available power as shown in Fig. 3. The servo drives control the servo motors, which communicate over the Modbus communication protocol. All these servo drives are connected in a daisy-chain configuration. These electrical actuators with the hydraulic actuators collectively consumed 8 Digital Output channels, 4 Analog Output channels and 01 Ethernet port.

The sensors play a vital role in fulfilling the feedback and safety requirements of the system. Various sensors were used as listed in Table 1 to monitor & control the operations of

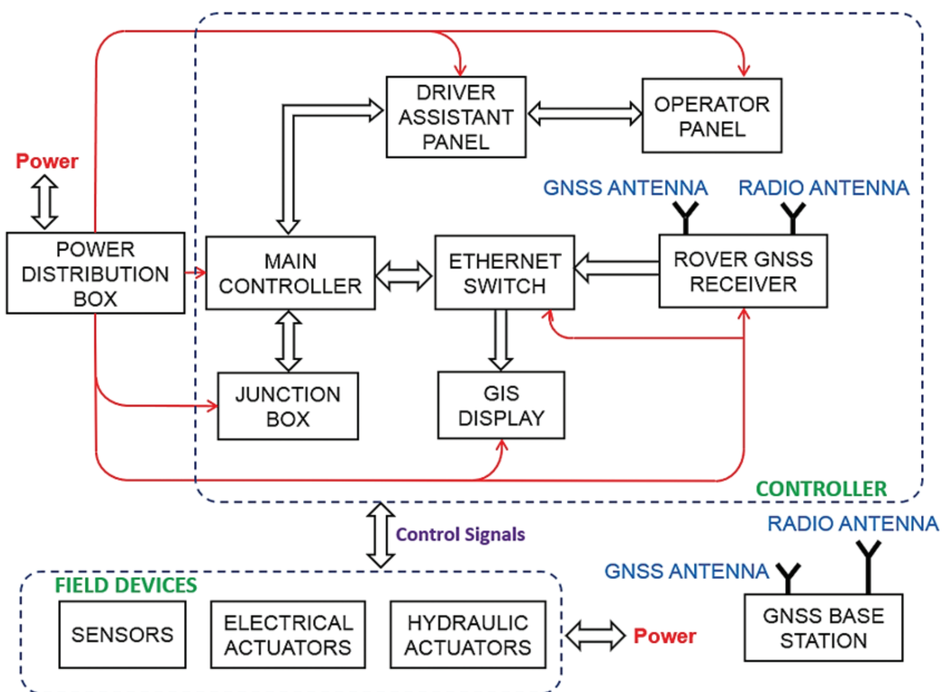

Figure 2. Block diagram for control system.

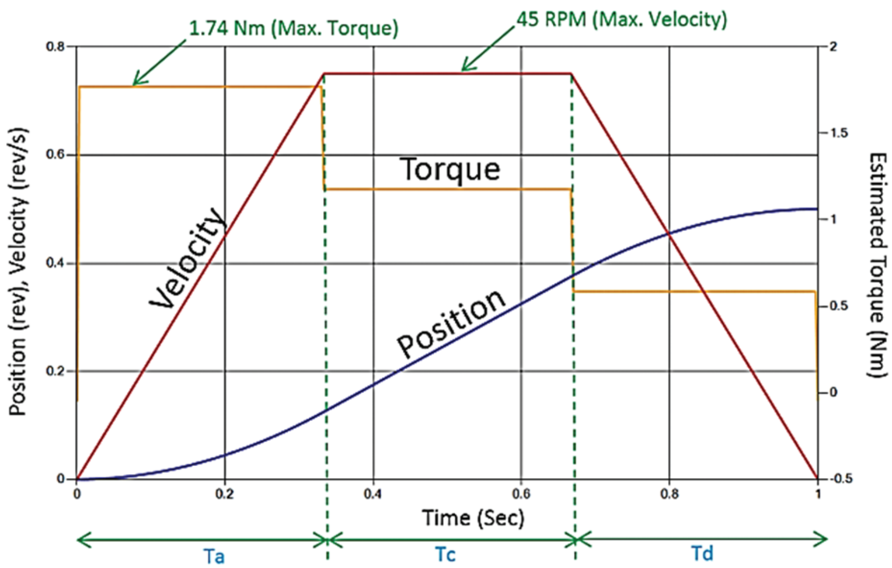

Figure 3. Motion profile curve.

Table 1. List of sensors used

Sensing object/ parameter	Type of material	Physical property	Sensor used
Rack Plate	Metallic	Non-contact	Inductive proxy
Object at different locations	Plastic	Contact	Limit switch
Object while arming	Plastic	Non-contact	Capacitive proxy
Arming position	-	Rotation	Absolute encoder
Pressure in hydraulic	Hydraulic oil	Pressure	Pressure transmitter
Vehicle longitudinal & transverse angle	-	Inclination	Inclinometer
Distance travelled by vehicle	-	Non-contact	Absolute encoder
Trenching speed	Magnetic	Non-contact	Hall effect sensor

Table 2. Actuators & sensors list

Description	IOs	Qty.
ACTUATORS		
3 Phase servo motors	Ethernet	6
Vfd	Ethernet	1
Hydraulic proportional valves	Analog & digital	4
Hydraulic directional control valves	Digital	3
SENSORS		
Limit switches	Digital input	26
Inductive proximity	Digital input	8
Capacitive proximity	Digital input	5
Stroke sensor	Analog input	2
Absolute Encoder	Ethernet	1
2 axis Inclinometer	Serial	1

mechanical structure. Limit switches, proximity switches, and encoders are part of the electronic control system that gives the real-time position of the objects and various mechanisms.

This system is based on a discrete position feedback mechanism. Various digital and analogue sensors give feedback about the state of mechanisms and health parameters of hydraulic and electrical actuators to the controller. Based on the state of mechanisms, the controller generates required actuating signals for hydraulic and electrical actuators. Pressure sensors, oil level switches, oil temperature sensors, oil filter clog switches, and stroke length measurement sensors are part of the hydraulic set-up, which gives the health status of the hydraulic system and gives parametric feedback to the controller.

Based on the selection of actuators & sensors (as listed in Table 2), a total of 52 DI, 11 DO, 8 AI, 5 AO, 2 Counters, 8 Ethernet ports and 1 Serial interface were required. Accordingly, necessary IO cards were selected considering functional and environmental compliance. As the field inputs & outputs are of different natures, it needs proper signal conditioning to interface signals with the processor. Hence, Signal conditioning was introduced to meet the interfacing requirement and provides necessary signal translation, isolation between field & logic side, filtering and impedance matching. The latest Intel-based centralized processing unit was used that fulfils our processing requirements, which centrally controls & monitors all the activities. The overall system design has been conceptualized around a 24 VDC power supply. All the modules, sensors, electrical drives and hydraulic valves have been selected such that they work on 24 VDC. Based on the overall power requirements of sub-systems, appropriate AC-DC and DC-DC power modules were selected.

A Differential Global Navigation Satellite System (DGNSS) receiver was used to identify the precise location of the laid objects. The sub-systems include GNSS Base Station, GNSS Rover Receiver and GIS system. An operator Panel has been provided for the Operator to control and monitor the operations during the Mission. It includes TFT Display along with different LEDs and Push Buttons. Driver assisting device is also provided in the Driver cabin to assist the Driver to control the vehicle's speed.

Diagnosis and debugging for any complex system are crucial tasks. We have used a centralized Junction Box that interfaces all the field signals with the Controller, which eases the diagnosis, debugging & maintenance of the system in case of any fault. End-to-end connectivity between all the sub-systems was achieved using a mil-grade harness, where all the necessary precautions like, the use of PTFE cables, copper braids, heat shrink sleeves, boots at the connector ends & backshell for cable protection at the connector end, were taken during the design of the harness scheme.

All military equipment should comply with the environmental specifications & EMC for electromagnetic radiation. JSS-55555[1] for environmental compliance & MIL-STD 461E[2] for EMC compliance are followed in the Indian scenario. Throughout the design & development process, it has been ensured that all the necessary precautions are taken to realize a system that complies with both these standards.

4. OPTIMISATION OF OBJECT LAYING RATE

All the sub-systems mentioned in the earlier section were installed on the vehicle. Controller, Rover GNSS receiver, Operator Panel, Driver Assistant Panel and GIS Display were interfaced with each other over ethernet using Ethernet Switch. After integration, system testing was necessary to meet the qualitative requirements. Initially, the automation software for the object laying system was developed to carry out activities in an operation in a sequential manner, as shown in Fig. 4. In this scenario, functional testing of the overall equipment was carried out in the field to ascertain the performance of each activity involved in the process. After technical trials, the object laying rate could not be achieved with the current strategy of executing the activities sequentially.

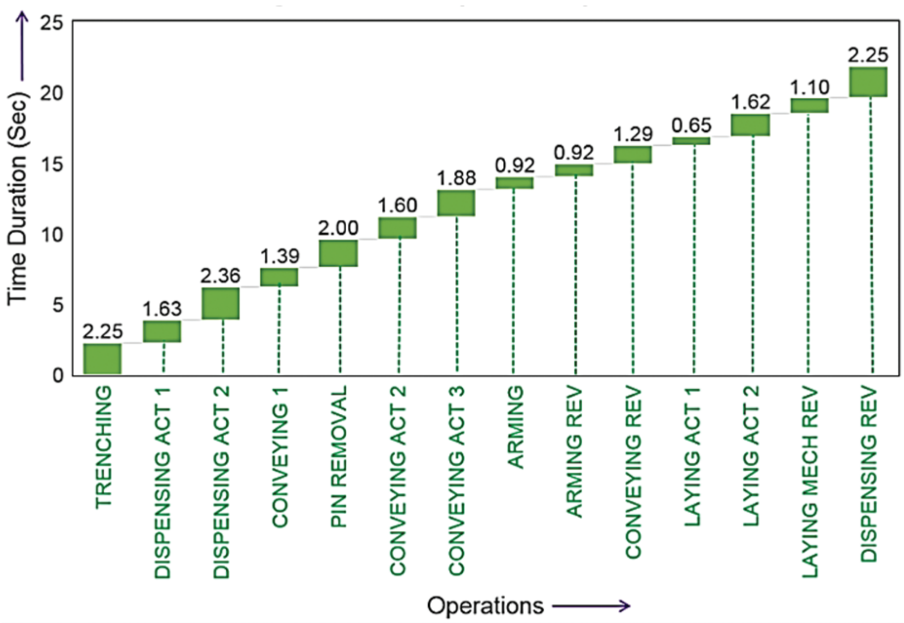

Figure 4. Timing chart for sequential activities.

Timing analysis was performed for individual operations and mutual exclusion of activities. Based on the results, it was found that certain activities can be carried out concurrently to reduce the time to lay an object. A simulation was carried out in LabView to analyse the gain in operation timing by implementing concurrent activities execution approach as shown in Fig. 5.

This simulation generated the optimized process timing for each activity. In addition, the data were collected in the field trials & data analysis was carried out for each operation of object laying. Using this data timing chart was prepared. With the help of domain expertise and field experience, activities were identified that could be carried out parallelly without compromising the safety aspect. The modification in automation software was to carry out concurrent activities in the operations. Again the functional testing of overall equipment was carried out in the field with the modified strategy. Figure 6 shows the timing cyclogram after modifications for effective object-laying time for each object. This figure also validates the results of the simulation done in Labview. Based on the vehicle speed, the number of objects laid per hour varies. However, considering the limitation of trenching mechanism observed during technical trials, the vehicle cannot be driven beyond the average speed of 3 kmph. As a result, in a practical scenario, the object laying rate will reduce.

5. LOCATION MARKING OF LAID OBJECTS

One of the qualitative requirements was to mark the location of the laid objects on the digital map with decimeter-level accuracy on a highly dynamic system with multiple factors adding up to the errors. Deviation in the Inter-object spacing

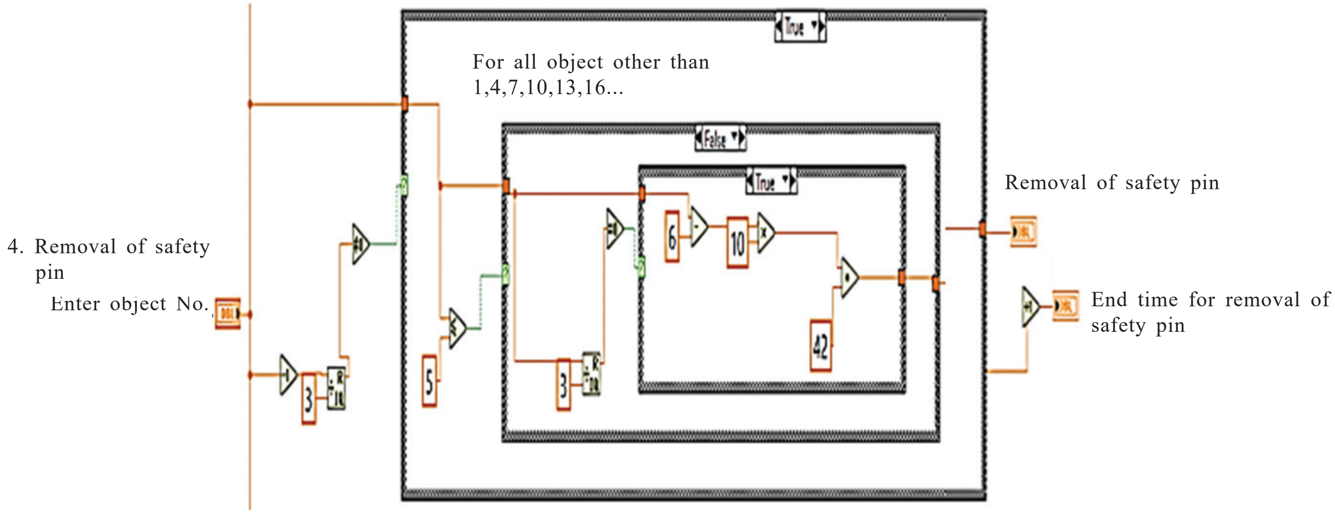

Figure 5. Sample labview program for simulation.

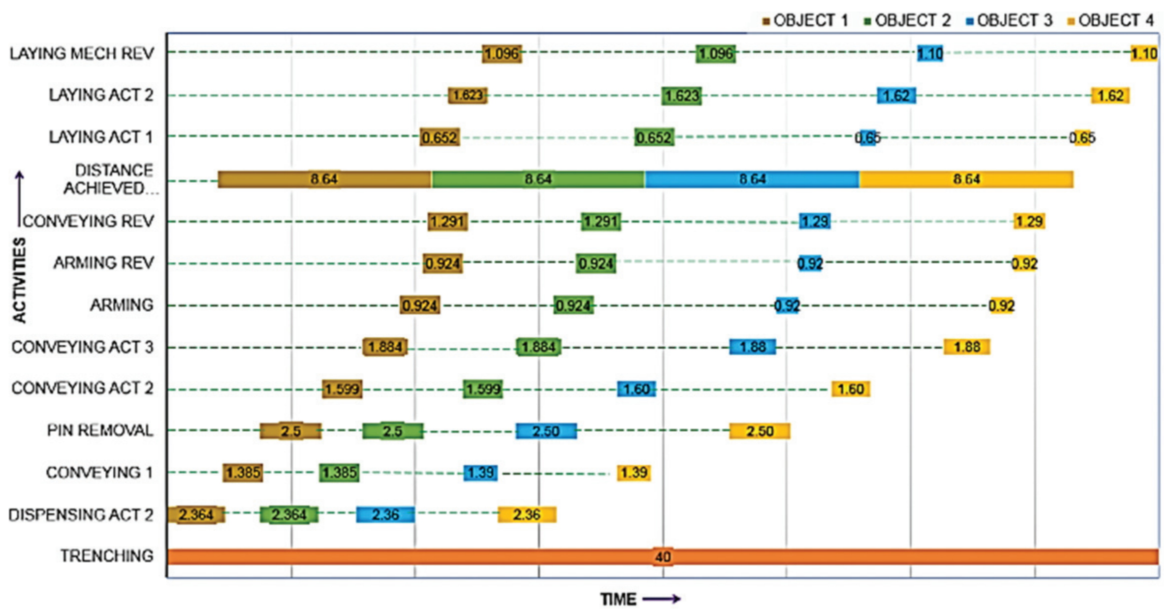

Figure 6. Timing chart for parallel activities.

was evaluated to find the error in the spacing as compared to the odometer and GNSS data.

The haversine formula is commonly used in navigation problems to calculate the distance between 2 points based on the length of the straight line between the two points on the longitude and latitude[15]. Haversine formula[16] uses the difference of changes in latitude (ΔLat) and longitude (ΔLong) in radians.

$$\Delta Lat = Latitude2 - Latitude \quad (1)$$

$$\Delta Long = Longitude2 - Longitude1 \quad (2)$$

From above Eqns, we can calculate the distance between two points using the formula in Eqn. (3).

$$Distance = 2\times R\times \arcsin\left(\sqrt{\left(\sin2\left(\Delta Lat / 2\right)+\cos\left(Latitude2\right)\times\cos\left(Latitude1\right)\times\sin2\left(\Delta Long / 2\right)\right)}\right) \quad (3)$$

where, R in Eqn. (3) is the radius of the earth which is 6371 km.

6. RESULTS & DISCUSSIONS

During the development process, one of the major challenges was to achieve the object laying rate. Activities were aligned parallelly wherever possible to reduce the time of each object and achieve the desired rate. Apart from this, the actuator's speed was optimized such that neither the system behaviour is sluggish nor fast to make the activity unbalanced. All these activities were carried out without compromising the safety aspect of the system and the crew.

Each object-laying process consists of 13 interdependent activities. Without implementing the parallel activities, each object takes 16-18 sec to complete all the activities. After implementing the logic for parallel activities, the time was reduced to 8.64 sec to complete all the activities for one object without compromising safety. A graph in Fig. 7 shows the comparative data of object laying rate in different terrains. It shows that the average laying rate achieved is highest in

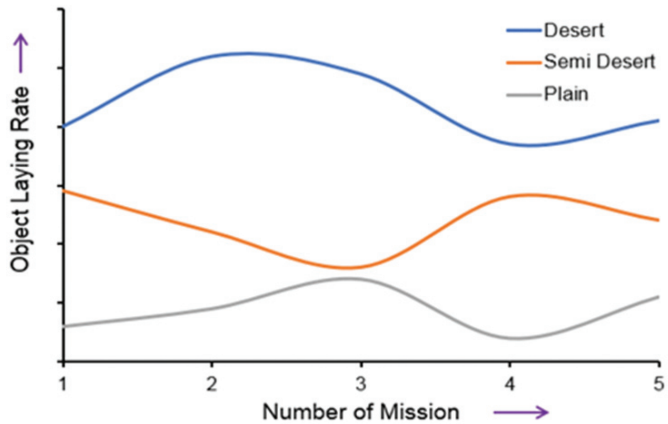

Figure 7. Object laying rate in different terrains.

Desert terrain and lowest in plains. Another challenge was the positional accuracy of the laid objects. Based on the Haversine formula mentioned in Section 5, data analysis was carried out for 30 objects as per Fig. 8. Equation 3 has been used here for calculating the inter-object spacing in centimetres using the latitude and longitude of the laid objects. This figure shows a deviation in the range of 10-15 % in the actual position of the object compared to the odometer & GNSS data, which is well within the permissible limits.

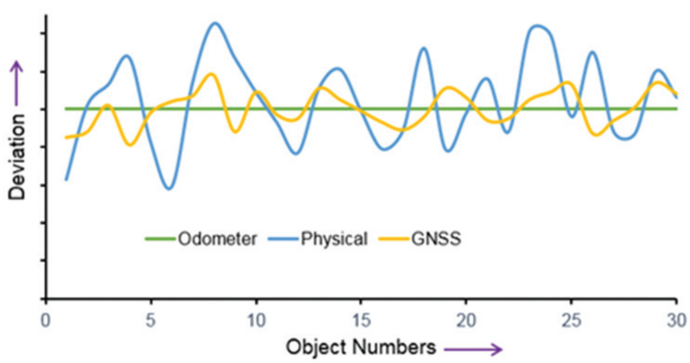

Figure 8. Inter-object spacing deviation.

Global Navigation Satellite System (GNSS), its augmentation techniques and the Geographical Mapping System are used extensively throughout the world for precisely locating the points on the earth's surface. We have evaluated these technologies for our applications and integrated them with this equipment to achieve this goal. The graph in Fig.9 shows the distribution of errors in object location marking against the number of laid objects in a given mission. Equation 3 is used here to calculate the positional accuracy in centimetres using the latitude and longitude of the objects. This graph implies that the accuracy of most objects is in the range of 0-30 cm location accuracy.

Additionally, the operations in such applications require a response from the controller in real-time to execute the sequence of operations in time without introducing any delay in the performance. This equipment involves handling, storage and transportation of such material. Hence, it poses a high risk to human life involved in this activity.

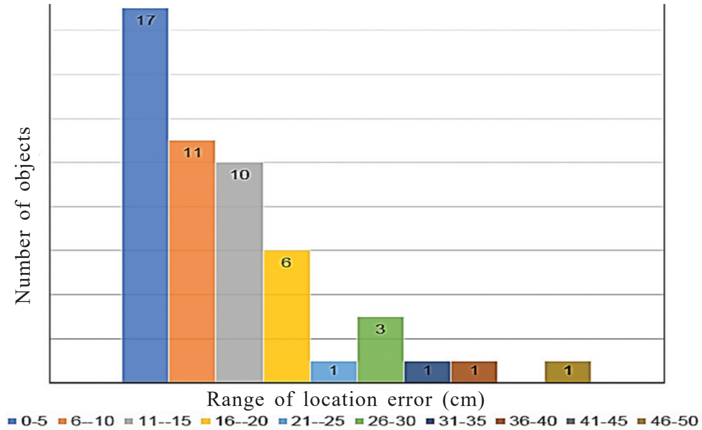

Figure 9. Location error distribution.

Special provisions were made during the design process to mitigate the risk of human life on board. The design of the mechanisms was made such that the vehicle and the crew were exposed to the armed object for the least possible duration during the whole process to avoid any catastrophe. Also, we have implemented software and hardware safety interlocks along with the redundancy of the sensors to positively monitor the status and position of the object at multiple locations throughout the object laying process. This ensures that no armed object during the entire operation of the object-laying process experiences the load beyond its permissible limit.

7. CONCLUSIONS

A multidisciplinary system is developed for military application, which includes compliance with stringent qualitative and environmental requirements. The space complexities and operational system dynamics were taken into consideration. This paper has explained the design philosophy and process optimization of a controller designed for a combat engineering system. Electrical drives & actuators with their mechanisms and sensors were used. IO cards, signal conditioning modules and power modules were selected considering the functional and environmental compliance. The system is developed to ease the diagnosis process, debugging and maintenance, in case of any fault. Improvements in object laying rate were carried out by doing activities concurrently to reduce the time by 54 % without compromising on the safety aspects of the crew. Analysis of sensors' data generated during exhaustive field trials was carried out to validate the process optimization methodology. The location of each laid object was marked with an average accuracy of 30 cm on the map for its safe and speedy recovery using Differential GNSS/ GIS.

The developed novel equipment has the advantages of reduced crew members and a fast, effortless and safe object-laying process. It also can precisely mark the location of the laid objects and generate a multilayered digitized map for future reference and retrieval.

8. FUTURE SCOPE OF WORK

Although the current realized system has performed and achieved all the qualitative and functional requirements, there is further scope for improvement in the system by upgrading the controller architecture to the latest technologies available in the market. The system can be thought of to be having a distributed control using ARM Cortex M4 Micro-controller with EtherCAT Slave Interface; which is an open, real-time and Ethernet network originally developed by Beckhoff[17], conduction cooled with additional features of modularity, scalability, lower latency, reduced cabling and particularly suited for space-constrained application. Also, the electrical actuator's drive can be interfaced using the EtherCAT bus, having its local controller controls the respective actuators. This will make the system faster, more cost-effective and easier to implement.

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He did timing analysis and improved the object laying process and experimentations for location marking accuracy for the present work.

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for the present work he prepared navigation system hardware for object location marking with the required accuracy. He was also involved in the analysis of the data & preparation of the graphs.

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He carried out the layout of the script. He was also involved in the analysis of the data & preparation of the graphs for the present work.

Mr Sandeep is a Senior Technical Officer at R&DE(E), DRDO, Pune, India. His work of interest includes embedded systems design, PCB prototyping and the development of ECAD software.
He was involved in overall system integration, testing and field trials for the present work.