Earthmoving Construction Automation with Military Applications: Past, Present and Future

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Abstract – Amongst increasing innovations in frontier engineering sciences, the advancements in Robotic and Autonomous Systems (RAS) has brought about a new horizon in construction applications. There is evidence of the increasing interest in RAS technologies in the civil construction sector being reflected in construction efforts of many military forces. In particular, Army or ground-based forces are frequently called upon to conduct construction tasks as part of military operations, tasks which could be partially or fully aided by the employment of RAS technologies. Along with recent advances in the Internet of Things (IoT) and cyber-physical system infrastructure, it is essential to examine the current maturity, technical feasibility, and affordability, as well as the challenges and future directions of the adoption and application of RAS to military construction. This paper presents a comprehensive survey and provides a contemporary and industry-independent overview on the state-of-the-art of earthmoving construction automation used in defence, spanning current world's best practice through to that which is predicted over the coming years.

Keywords – Construction automation; Earthmoving; Defence; Robotic and Autonomous Systems.

1 Introduction

Construction automation represents the field of research and development focused on improving construction processes by applying the principles of industrial automation [1-3]. Among general construction processes, there have been resurgent interests in the automation of earthmoving equipment such as wheel loaders and bulldozers. New thinking is occurring within a framework of modelling of control, planning and artificial intelligence with the use of sensing and information technologies [4,5] in combination with the frameworks for understanding robotic and autonomous systems (RAS) as applied to construction automation [6]. To this end, a great deal of research and development has been devoted to raising the level of autonomy of construction plant, in both civilian and military domains, to improve their efficiency, productivity, quality and reliability [7].

Robotic and autonomous systems tailored for the military call upon the ability to integrate sensors, vision imaging, actuators, end-effector manipulation, computer control and human interface for operations in unstructured, difficult and hazardous conditions. Army construction tasks for enhancing force protection include such earthmoving tasks as filling of protective barriers (HESCO baskets), building dirt bunding structures, as well as anti-tank ditches and trenching. For such tasks a variety of heavy construction machinery such as excavators, bulldozers, wheel loaders, graders and articulated dump trucks etc. have been customised to meet the special requirements of the military.

With the demand on combat engineering capability to provide greater force protection with more rapid rates of construction, there is an increasing requirement for the transformation of combat engineering construction plant into more autonomous systems. Studies in this field therefore have recently received much research interest. In [8,9], surveys of RAS used in military applications have been conducted with discussion on Unmanned Ground Vehicles (UGV) and air/sea-based robotic vehicles. However, the focus therein was mainly on combat and logistic operations rather than construction. Given the rapid developments in military construction automation with the use of high-mobility ground-based platforms, human-machine and machine-machine interfaces, teleoperation and control systems, data transmission systems, perception and manipulation capabilities [10], the survey presented in this paper aims to provide an overview and analysis on the state-of-the-art of earthmoving construction automation used for Army applications. This survey will cover construction tasks and corresponding platforms in alignment with defence applications. Platforms of interest include excavators, bulldozers and wheel loaders in tele-operated, shared-control, semi-autonomous, or autonomous modes of operation.

Most earthmoving tasks with their array of platforms and equipment are cooperatively coordinated within construction operations. On one hand, recent developments in networked robotics and the integration of IoT within intelligent digital infrastructure [11,12], could afford task coordination efficiency benefits to such construction operations. On the other hand, with digitally connected systems there also arises the inherent cyber risk compared to the traditional ones.

2 RAS in Ground-Based Construction – A Review

The application of RAS to typical platforms such as excavators, bulldozers and wheel loaders is evaluated through studies in teleoperation and autonomous operations [13] on the basis of the technology readiness level (TRL) framework [14] of 9 levels, from basic research (TRL 1) to operational deployment (TRL 9).

2.1 Excavator

2.1.1 Remote Control and Teleoperation

In remote control and teleoperation, a key challenge is to develop a reliable human-machine interaction model and real-time data feedback. One of the earliest studies in this direction was conducted in the early 1990’s by Burks *et al.* [15] in a study funded by the U.S. Army with the aim to find principles for the teleoperation of excavators to retrieve unexploded ordnance and radioactive waste (TRL1-2). At the subsystem development level (TRL 3-6), various studies have been conducted to develop models and prototypes for tele-operated excavators. In 1995, Ohmori and Mano introduced the concept of master-subordinate-slave tele-earthwork system, which replaced a human operator using a teleoperation system known as RoboQ [16]. Yokoi *et al.* (2003) developed a master-slave system which used a humanoid robot to operate and control a backhoe [17]. Teleoperation involving tele-grasping sensory perception, which is based on a master-slave teleoperation concept of a grapple-attached mini excavator, has been carried out by a group of researchers in Gifu University, Japan [18]. The proposed control system significantly improved the slow grasping of a soft object by improving the sense of grasping through the application of force feedback [19]. Such control requires the use of pressure and displacement sensors to be attached to the mini excavator. The research was verified by simulation and experiments confirmed the validity of the control system. Later, Yusof *et al.* (2012) conducted studies on operator sensitivity to various modalities, where the perception of the operator for each type of feedback was evaluated by using common 2D, 3D and virtual visual feedback [20]. Precision grasping was also tested by utilising auditory feedback, along with force feedback [21]. Kim *et al.* (2008) proposed an interesting study of controlling an excavator using the movement of the human arm [22] while Sasaki and Kawashima (2008) developed a remote controlled pneumatic robotic system, which can replace a human operator [23]. The benefit of the remote controlled operations conducted at local construction sites has been quantified by the increase in work efficiency of more than 50% compared to the direct operation of the excavator. The same concept was studied by using a teleoperated electro-hydraulic actuator, equipped with a 2.4 GHz remotely controlled system [24].

At the level of Integrated Pilot System Demonstrated (TRL 7-8), teleoperation of excavators has been tested in Japan for events involving post volcanic and earthquake disaster recovery [25], which was a milestone for application of RAS to a large-scale unmanned construction operation of post disaster recovery works.

2.1.2 Autonomous Excavation

Studies in autonomous excavation started in 1986 at CMU in which a prototype named Robotic Excavator (REX) was developed [26]. REX combined integrated sensing, modelling, planning, simulation, and action specifically to unearth buried utility piping at TRL 1-2. Human interfaces to REX included a joystick, keyboard and animated display, while a rugged hydraulic arm was appended to a four-link backhoe for actuation. Since then, a large number of studies have been conducted addressing various aspects of autonomous excavation. Excavator kinematics and dynamics can be analysed and derived by assigning coordinate systems to the manipulator configuration of boom, arm and bucket, and applying the Newton-Euler formula to the local coordinate frame for each link in succession as a free body [27]. In [28], full kinematic and dynamic models of the excavator arm represented as a planar manipulator with three degrees of freedom (boom, arm and bucket) are derived using the Lagrangian formulation. A virtual model for excavators was developed for an earthworks site, whose terrain geometry is continuously updated as excavation and earth-moving continue until completion, is used to study the interaction between the excavator and its surrounding environment [29]. In a recent work [30], the operation function is modelled through analysis of deterministic processes and trajectories of the relieving tool.

At the TRL 3-6 level, a number of studies focused on general control techniques for autonomous excavators. In [31], Bradley *et al.* (1989) discussed the developments necessary to operate a simple backhoe arm. Experimental studies were presented in [32] on mechanics of planetary excavation. In [33], the control of an intelligent excavator for autonomous digging in difficult ground was conducted on a mini excavator. Malaguti (1994) [34] proposed a decentralised variable structure control of joints, including the actuator dynamics, and considered the possibility to adapt the control dynamics on the system disturbs. In [35], the force and position control problem was addressed for electrohydraulic systems of a robotic excavator. The idea of controlling the force and position relationship was proposed by Ha *et al*. (2000) in terms of impedance control for a hydraulically actuated robotic excavator [36]. The control technique being implemented on a Komatsu 1.5-tonne excavator, demonstrated that the proposed control technique could provide robust performance when employed in autonomous excavation mode with soil contact considerations. The impedance control method was further developed by Tazafoli *et al.* [37]. Recently, partial automated blade control has been studied in [38] to control one of the excavator’s work cylinders while the machine operator controls the rest of non-automated work cylinders. A Time-Delay Control with Switching Action (TDCSA) using an integral sliding surface was proposed for the control of a 21-tonne robotic excavator [39], whereby analysis and experiments showed that using an integral sliding surface for the switching action of TDCSA was better than using a Proportional Derivative-type sliding surface. The proposed controller was applied to the linear motion of the entire excavator at the same speed level as that of a skilful human operator. In [40], the Time-Varying Sliding Mode Controller (TVSMC) combined with a fuzzy algorithm has been used for an unmanned excavator system. The computer control system [41] was implemented on a 1.5 tonne 3-link (boom, arm and bucket) excavator. Developments in high-level control have been studied for task level execution such as positioning, path planning and disturbance mitigation. In [42], Matsuike *et al.* (1996) developed an excavation control system, as a supporting system for large-depth excavation, in which the excavator was exactly positioned with the error being less than 30-50 mm. A control architecture was developed in [43] for autonomous execution of some typical excavation tasks in construction. Using the same platform, Maeda [44] dealt with disturbances arising from a material removal process by proposing the Iterative Learning Control (ILC) with a PD-type learning function as a predictive controller, to achieve a desired cut profile with non-monotonic transients which converged faster by learning disturbances directly from command discrepancies.

Interactions between construction tools and the soil represent highly-non-linear and dynamic processes [45]. There are two strategies to the problem of time varying soil-tool interaction forces: (i) to treat it as a disturbance and design a suitable controller for compensation, or (ii) to design an efficient soil-tool interaction model which can accurately model the dynamics of excavation in real time. One of the main challenges in designing an efficient, robust, adaptive controller for the excavator, emanate from the machine-environment interaction dynamics as the largest contributor of time-varying forces in the system. Complex rheological models capable of computing accurately soil behaviour require a large amount of computational time and hence are infeasible for a real-time dynamic controller [46]. To this end, some recent models have been proposed to predict soil-tool interaction sufficiently well. A 3D semi-infinite soil medium is often replaced by a non-coupled discrete rheological model, independent of its structural elements [47].

As the soil parameters required for accurate modelling are difficult to obtain experimentally, efficient methods must be used for soil parameter estimation [48]. A fuzzy system was proposed, using no information on soil conditions, and solutions offered were claimed to be sub-optimal [49]. Different tool-soil interaction models exist, e.g. the Finite Earthmoving Equation (FEE) model and its modifications [50], and the Linear Lumped Model [51], which is computationally more effective than the FEE. After all, soil behaviour by its nature is complex and the variation of some parameters can greatly alter the soil conditions. Sensors can therefore provide information to compensate for such variations and controllers should be able to handle such disturbances, a detailed survey of which can be found in [52].

Towards full-scale autonomous excavation at TRL level 7-8, a pioneer system was demonstrated by Stenz *et al.* (1999) [53]. The system is the first fully autonomous loading system for excavators being capable of loading trucks with soft material at the speed of an expert human operator. In another study, Yahya (2008) proposed the concept of parameter identification, as a key requirement in the field of automated control of unmanned excavators [54]. An automated excavating prototype was developed in [55] for excavating ditches for drainage. This system was composed of two sub-systems, an automatic surface finishing system and a laser guide system for excavating ditches up to 8 km in length. A vision-based control system for a tracked mobile robot such as an excavator was developed in [56], including several controllers that can be collaboratively operated to move the mobile platform from a starting position to a target location. A prototype of a autonomous hydraulic excavator was introduced to improve the basic technologies of construction machinery such as hydraulic shovels [57], which was also able to complete the autonomous loading of a crawler dump truck. More recently, a prototype system based on a Volvo EW 180B excavator has been reported as part of the autonomous excavator project THOR (Terraforming Heavy Outdoor Robot) with the goal of developing a construction machine which performs landscaping on a construction site without an operator [58].

2.2 Bulldozer

2.2.1 Principles and Subsystems

At TRL 1-2, pioneering work on autonomous bulldozers started several decades ago, as was the case for excavators. Muro (1988) introduced an automatically controlled system for maximising productivity of a dozer running on soft terrain [59], whereby a microcomputer was used to obtain information of terrain properties and vehicle states so that based on that information, optimum drawbar-pull and slip ratios could be computed during digging. Since then, various studies have been conducted, focussed on different research topics such as modelling and control, position and pose estimation, machine-soil interaction, navigation, teleoperation, simulation and real world applications.

At TRL 3-5, Olsen and Bone [60] investigated the modelling of a robotic bulldozing operation for the purpose of autonomous control. Later, in [61], the bulldozer's workflow was modelled using an adaptive neural network to simulate and predict the dependence of the resistive strain of gauge bogie displacement on the dig depth and trolley speed dynamically. The force acting on the blade was first modelled and a model-based adaptive control strategy was then proposed for controlling the blade. The control of the dozer blade could be addressed using fuzzy theory for the semi-automatic control of a real-world bulldozer [62]. Meanwhile, a control strategy for hybrid engines of tracked bulldozers was also addressed in [63], based on a multi-objective design optimisation of the engine control parameters to minimise fuel consumption.

In the soil cutting and pushing process, the dozer blade experiences soil resistance owing to friction, cohesion and adhesion between the blade and soil, and the soil and ground [64]. The forces acting on the blade vary in a complicated manner that may deteriorate the performance of the bulldozer. The resistance or draft force problem has been tackled either empirically [65] or using numerical methods [66], whereby a cohesive bond force model was introduced in which the microscopic behaviour of the cohesive force was evaluated against macroscopic shear failure characteristics. The dynamic behaviour has also been taken into account by considering velocity and acceleration in the model [67]. Numerical studies were conducted with the finite element method for soil mechanics and the failure zone using various models including constitutive equations of soil failure [68] and an elasto-plastic constitutive model [69]. In simulation and navigation, analyses of the driving system of a crawler bulldozer were carried out with two types of pavement, clay and hard, taking into account the driving force. The results provided a reference for improving the performance of the crawler bulldozer drive system [70]. Recently, a guidance system for the bulldozer has been developed using sensor fusion. The integration of an Inertial Measurement Unit (IMU) with two Real Time Kinematic (RTK) global positioning systems (GPS) allowed accurate estimation of the pose and position of the bulldozer blade, providing feedback to the navigation system [71]. Experiments on a full-scale bulldozer were implemented to validate the approach.

2.2.2 Integrated Pilot Systems

At TRL 7-8, a group of 20 prototype bulldozer robots were built to develop autonomous and cooperative capabilities [72], using tank-like treads driven by two independent actuators, and equipped with a scoop which can be lifted up and down and tilted back and forth. They also have a one degree-of-freedom head which constantly rotates with various sensors mounted onboard. Experiments were performed on an artificial lunar surface and the results were promising for various planetary tasks. Apart from space programs, autonomous bulldozers have been developed for surveillance, mining and construction. In [73], Moteki *et al.* have adapted the unmanned construction system technology to build semi-autonomous bulldozers for operations in a disaster situation. More recently, ASI Robotics Inc. has developed a system of robotic hardware components that allow users to control a vehicle in both modes, manual and autonomous modes. The system consists of NAV™ (the onboard computer and communications system), Vantage® (obstacle detection and avoidance features), and Mobius™ (command and control software) [74]. Together, these components form a universal automation solution for vehicles of different geometries, sizes, and applications.

2.3 Loader

Autonomous loaders are considered as an integrated system of hydraulic, mechanical and electronic subsystems. Being widely used at construction sites, these machines have received much research interest to continuously improve their performance and autonomy level. At TRL 1-2, since 1990's, the study on control and planning of frond-end loaders has become active [75]. By using a microcomputer, the computer controller is capable of positioning the linkage in either Cartesian or angular coordinate motion with the ability to store and recall trajectories. Since then, a number of studies have been conducted on model loaders, which are essential for improving their performance and autonomy level to TRL 3-4. Worley and Saponara (2008) presented a simplified dynamic model of a wheel-type loader to accelerate the structural design and analysis of the boom and bucket linkage subsystems [76]. The lateral dynamics of skid-steering high-speed tracked vehicles were presented, with a nonlinear track terrain model derived from classical terra-mechanics [77]. Recently, both kinematic and dynamic models of a skid-steered robot were identified via a learning process based on the Extended Kalman Filter and an efficient neural network formulation [78]. In terms of machine control, an automated digging control system (ADCS) for a wheel loader was developed using a behaviour-based control structure combined with fuzzy logic, and implemented on a Caterpillar 980G wheel loader [79]. A closed-loop digital velocity control was successfully implemented for those objectives with the results validated by experiments on a large Caterpillar 990 wheel loader, as reported in [80]. In another approach, an H-infinity based robust control design combined with feedback linearization was presented for an automatic bucket levelling mechanism wherein robustness of the controller design was validated in simulation by using a complete nonlinear model of the wheel loader [81].

At SRL levels 7-8 for integrated systems, Volvo Construction Equipment, developed a prototype of a fully autonomous haulage truck and wheel loader, and demonstrated it in 2016 [82]. Most recently, a fully autonomous track loader has been developed and tested in the field by Built Robotics Inc. taking advantage of the significant advances in self-driving car technologies. The developed software and sensor suite can transform off-the-shelf loaders and excavators into robotic platforms that can undertake earthmoving tasks with precision, and for hours without a break [83].

3 Earthmoving Construction Automation in Military Applications

3.1 EOD and landmine detection

One of the earliest RAS used in military applications was reported in 1992 [15] for the Small Emplacement Excavator (SEE), a ruggedized military vehicle with backhoe and front loader used by the U.S. Army for explosive ordnance disposal (EOD), combat engineering, and general utility excavation activities. Its features include teleoperated driving, a telerobotic backhoe with four degrees-of-freedom, and a teleoperated front loader with two degrees-of-freedom on the bucket. In [84], a terrain scanning robot can autonomously manipulate a typical handheld detector for remote sensing of buried landmines using map building and path planning implemented in real-time software. A commercial Modular Robotic Control System (MRCS) was first integrated onto a Nemesis HD Robotic Platform for the tasks of ground clearance and landmine detection Wetzel *et al*. (2006) [85]. It was then installed on the 924G Bucket Loader, shown in Fig. 1, for various construction operations including excavating, digging, lifting/loading, stripping, levelling, and stockpiling.

Another commercial-off-the-self robotic kit, the Appliqué Robotics Kit (ARK), was also designed to allow the modification of existing plant to remote controllable with the minimal modification of the host vehicle or its electro-hydraulic system. In [86], the ARK was installed on a front end loader/backhoe used for excavation of small emplacements, material handling, and general construction tasks as shown in Fig. 2. Experimental results showed that this RAS technology was suitable for operational use and supported hasty route clearance operations for the military. These unmanned ground vehicles can also be used for other purposes such as surveillance; remote monitoring; engineering and military policing tasks; and chemical, biological, radiological, and nuclear (CBRN) defence.

Fig. 1: MRCS installed on the 924G Bucket Loader [85].

Fig. 2: An Army loader/backhoe installed with ARK [86].

3.2 Earthwork for military purposes

Earthwork operations have been used for centuries as part of military defensive operations. This could be in the form of moats, foxholes, or bunkers to protect equipment and personnel. It is not difficult to organize such work as it does not involve technology and can be performed with rudimentary equipment. A more permanent form of earthwork may have facing materials on the parapet that makes up the higher part of the earthen embankment. This could be constructed with stones, sandbags, wood, or any other material. Such protection requires additional time and is rarely a form adapted in actual battle conditions. Other forms of military earthwork include moats, which are often built around inhabited areas and filled with water to slow down the enemy. Modern day warfare uses the same method to create tank trenches, quite often for miles to slow down an armoured column assault.

A *Forward Operating Base* (FOB) is a secured forward military position, commonly a military base that is used to support tactical operations. A FOB may or may not contain an airfield, hospital, or other facilities. The base may be used for an extended period of time. FOBs are traditionally supported by Main Operating Bases that are required to provide backup support to them. A FOB also improves reaction time at the local level rather than having all troops in the Main Operating Base. In its most basic form, a FOB consists of a ring of barbed wire around a position with a fortified entry control point. More advanced FOBs include an assembly of earthen dams, concrete barriers, gates, watchtowers, bunkers and other force protection infrastructure. They are often built from special retaining or shoring walls called bastions for defence. Figure 3 shows construction of a HESCO bastion by US Marine Corps with the help of an excavator [87], for a FOB in Afghanistan's Delaram District.

Fig. 3: Building Delaram FOB [87]

A common example of military earthwork is to put in place a *barrier* between the force and the enemy for force protection. The basic form of any such earthwork operation is a mound of earth or embankment rising above the general ground level. This embankment is formed from earth that is excavated in the same locale, thus simultaneously creating a ditch. The ditch adds to the height and depth available for protection. A *foxhole* is the simplest form of military earthwork normally dug in position by a soldier who will use it for self-protection in battle. A section of soldiers may connect up their individual foxholes to form a continuous trench that can be used to facilitate the supply of ammunition and allow communication ferrying with commanders.

The *HESCO bastion* is a modern gabion primarily used for military fortification. It is made up of a collapsible wire mesh basket and a heavy-duty geo-fabric liner. They are used as a semi-permanent blast wall against explosions or small-arms fire and used for FOB wall constructions as in Figure 3. One of the best features of HESCO is its ease in setting up. Flat pack and concertinaed HESCO can be pulled off a truck and erected quickly. With a front-end loader or excavator used to fill the baskets with dirt, sand or gravel, a wall can be built within hours and is much quicker than sand bagging.

Antitank ditches are constructed to strengthen prepared defensive positions. As they are costly in time and effort to construct, much is gained if the excavation can be made by means of cratering charges. An antitank ditch must be wide enough to stop an enemy tank, and it may be improved by placing a log hurdle on the enemy side and the spoil on the friendly side. Forming such ditches can be improved by digging the friendly side nearly vertical. Antitank ditches are usually triangular, rectangular, or trapezoidal in cross section and have a low parapet on the defender's side. Their dimensions vary and they are often reveted or contain water. Figure 4 shows a British Army Terrier combat vehicle employed for trench digging. Manufactured by BAE, it has drive-by-wire and teleoperation capability, equipped with a remotely controllable hydraulic front bucket and excavating arm. It is used remotely by operators for clearing routes, creating cover, digging anti-tank ditches and trenches under harsh conditions [88].

Fig. 4: Teleoperated trench digging [88].

3.3 Military use of RAS on earthmoving platforms.

The application of RAS is becoming more widely used on legacy earth moving plant within the military. Autonomous land vehicles have been developed for navigation, reconnaissance, surveillance, and target acquisition. Recently, the US Army has tested the autonomous vehicle technology in its fleet of logistical vehicles. The leader follower technique in robotic formation was used to form a convoy of trucks equipped with a laser-based sensor (LIDAR) used for maintaining the distance clearance. Figure 5 shows a test scenario to demonstrate the concept of V2I (Vehicle To Infrastructure) that allows for a formation of one manned truck leading seven driverless connected vehicles [89].

Fig. 5: The US Army is testing a "leader-follower" system that will employ up to 8 convoy vehicles [89].

For military use, bulldozer blades can be optionally fitted to platforms including, such as artillery tractors of Type 73 or M8 Tractor. Dozer blades can also be mounted on main battle tanks, where it can be used to clear antitank obstacles, mines, and dig improvised shelters. Combat applications for dozer blades include clearing battlefield obstacles and preparing fire positions. Bulldozers employed for combat engineering roles are often fitted with armour to protect the driver from small arms fire and debris, enabling bulldozers to operate in combat zones. The Israeli Army Engineering Corps have also completed an extensive project to equip unmanned bulldozers with autonomous capabilities, as shown in Fig. 6, to carry out specialized tasks for earth moving, clearing terrain obstacles, opening routes and detonating explosive charges [90]. Front end loaders are also commonly used in military applications for constructing and removing road blocks and building bases and fortifications.

Fig. 6: Robotic bulldozer used by Israel Defence Forces [90].

4 Construction Automation – A Projection Regarding Military Applications

Since the last decade of the 20th century, there has emerged increasing research evidence for the viability of RAS in autonomous construction tasks including the more challenging problem of autonomous excavation [91, 92]. The enabling technologies arising from the research and development into RAS for automating construction tasks using platforms such as excavators, dozers and loaders have become much more mature and better integrated, providing a foundation for the next stage of growth in off-the-shelf products. In addition, embracing the recent advances in manufacturing with Industrie 4.0 [93], cloud computing, cyber-physical systems and IoT, tomorrow’s technologies for construction automation can be foreseen in the improvement of construction site efficiency with a plethora of technologies, systems, data and services.

Looking ahead at the use of RAS in construction, Kendall Jones, the Editor-in-Chief of the ConstructConnect blog [94], emphasises efficiency and accuracy, envisaging an automated construction site in the future that will have a fleet of dozers, graders, and excavators undertaking site works without any operators behind the cabin controls, and some without cabins.

During the Second World War, when the U.S. and Germany started to develop Unmanned Air Vehicles (UAVs), military robotics has made tremendous progress. As increasing evidence of defence interest in autonomous systems, in 2001 the US Congress mandated that, “By 2010, one third of the operational deep-strike force aircraft fleet are unmanned, and by 2015, one-third of the operational ground combat vehicles are unmanned”[1]. Unmanned Ground Vehicles (UGVs) are becoming more engaged in a variety of missions including Explosive Ordnance Disposal (EOD), combat engineering, reconnaissance, and civil works. RAS, including ground, aerial, underwater, amphibious vehicles [95], anti-munition systems, armed robots, cyber-attack and defence systems are anticipated to become a central piece of military operations in the years ahead.

According to Randall Steeb, a senior scientist at Rand Corporation, commented that the US Army’s Future Combat Systems (FCS) program emphasised the use of autonomous, armed cooperative robots [96]. While eventually cancelled, the FCS program was further evidence of a growing interest in military application of autonomous systems. Cooperation of unmanned platforms with humans and inhabited machines in construction has been gaining interest in the RAS community. In parallel with this is the widening use of the military concept of teaming of unmanned vehicles [13]. For example, the flexible leader-follower formation of skid-steered tracked vehicles towing polar sleds has been studied with a developed dynamic model and a proposed control architecture. The results have shown that the follower tractor maintains the flexible formation but keeps its payload stable while the leader experiences large oscillations of its drawbar arm indicating potential payload instability [97]. In this context, efficient and adaptive RAS, along with artificial intelligence techniques and ubiquitous communication networks can effectively support the cooperation to meet the expectations of ever changing operational environments and recover from disturbances.

In construction and infrastructure, the emerging field of IoT is directly applicable to the technologies for interconnected systems, consisting of several communication layers, such as in the driverless vehicle technologies, or in advanced manufacturing. IoT is a paradigm that considers the pervasive presence of a variety of objects possessing digital intelligence in an environment. These make themselves recognizable and can behave intelligently by making context related decisions thanks to information aggregation and sharing with other objects.

Teaming of different platforms in military construction will find its root in the development of methodologies and techniques for interconnected systems [98] and the application of intelligence science, data science and IoT or cyber-physical systems [99]. In the military domain, IoT finds direct applications in such operations that are often conducted in a complex,

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[1] Section 220(a) (2) of the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001 (as enacted into law by Public Law 106–398; 114 Statute 1654A–38).

multidimensional, highly dynamic and disruptive environment, e.g. a FOB, where commanders have to accurately and promptly assess the situation, to gather all possible information sources to obtain the most complete and relevant picture in order to make decisions [100]. Scenarios for use of IoT in warfare conditions may include its applications to support tactical reconnaissance, smart FOBs that incorporate IoT technologies in force protection at bases as well as maritime and littoral environments, health and personnel monitoring, and equipment maintenance. The technical challenges will rest with reliability and dependability, especially when IoT becomes mission critical; actuation of IoT devices, especially with real-time requirements; power for their tactical deployment; architectural aspects of military IoT infrastructure including security, information, and communication architectures; and interoperability and integration of disparate technologies.

5 Conclusion

We have comprehensively surveyed the use of RAS in earthmoving construction machinery with applications to the land force. Typical automated platforms such as excavators, bulldozers and front-end loaders are reviewed with regard to modeling, low and high levels of control, their system architecture, sensing and navigation, tool-soil interactions, simulation and experiments from laboratory set-ups to full-scale field tests, in remotely controlled, teleoperated, semi-autonomous and autonomous modes of operation. The developments of RAS for these platforms have been perused from several decades till the present day and, this survey has provided an overview of these in terms of their technology maturity and systems readiness. These developments range from basic research through to operationally employed systems.

Acknowledgements

Support received from the Land Division, Defence Science and Technology Group of the Australian Government and the UTS Distinguished Visiting Scholar scheme is gratefully acknowledged. The authors would like to thank Prof. Miroslaw Skibniewski and Mr Stephen Baker for fruitful discussion and improvements during the preparation of this survey.

References

[1] Skibniewski, M. “Current status of Construction Automation and Robotics in the United States of America,” *Proc. 9th Int. Symp. Automation and Robotics in Construction,* Tokyo Japan. 1992. Doi 10.22260/ISARC1992/0003

[2] Gatton, T. and Kearney, F. “Automation and Robotics in Construction: Japanese Research and Development,” *US Army Corps of Engineers*, Technical Report, M90-03, pages 9-10, United States, 1989.

[3] Ahmed, N., Hong, A., Ku, N., Moon, S.-K. and Moon, S.-W. “Technical review of automated system application to earthworks in Australia”. In *Proceedings of the 34th Intl. Symp. on Auto. and Rob. in Const.* (ISARC’17), pages 594-601, Taipei, Taiwan, 2017. Doi 10.22260/ISARC2017/0083

[4] Dadhich, S., Bodin, U. and Andersson U. “Key challenges in automation of earth moving machines”. *Automation in Construction*, 68: 212-222, 2016. Doi 10.1016/j.autcon.2016.05.009

[5] Azar, E.R. and Kamat, V.R. “Earthmoving equipment automation: a review of technical advances and future outlook”. *Journal of Information Technologies in Construction*, 22(13): 247-265, 2017. http://www.itcon.org/2017/13.

[6] Balaguer, C. and Abderrahim, M. “Trends in Robotics and Automation in Construction,” in *Robotics and Automation in Construction* (Eds. C. Balaguer and M. Abderrahim) InTech 2008. Doi 10.5772/5865

[7] Ha, Q.P., Wang, X., Bock, T. and Balaguer, C. “Editorial” *Automation in Construction*, 59: 97-98, 2015. Doi 10.1016/j.autcon.2015.09.001.

[8] Lin, P., Bekey, G. and Abney, K. *Autonomous military robotics: Risk, ethics, and design*, California Polytechnic State University, San Luis Obispo, 2008. http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1001&context=phil_fac

[9] Sapaty, P. "Military robotics: latest trends and spatial grasp solutions." *International Journal of Advanced Research in Artificial Intelligence*, 4(4): 9-18, 2015. Doi 10.14569/IJARAI.2015.040402

[10] Budny, E., Szynkarczyk, P. and Wrona, J. "Unmanned Ground Military and Construction Systems Technology Gaps Exploration", *The 34th Int. Symp. Automation and Robotics in Construction* (ISARC), pp. 577-581, Taipei, Taiwan, 2017. Doi 10.22260/ISARC2017/0080

[11] Ray, P. P. “Internet of Robotic Things: Concept, Technologies, and Challenges,” *IEEE Access*, 4: 9489-9500, 2016. Doi 10.1109/ACCESS.2017.2647747

[12] Kochovski, P. and Stankovski, V. “Supporting smart construction with dependable edge computing infrastructures and applications”. *Automation in Construction*, 85: 182-192, 2018. Doi 10.1016/j.autcon.2017.10.008

[13] Finn A. and Scheding, S. *Developments and Challenges for Autonomous Unmanned Vehicles*, Springer, 2010 ISBN 978-3-642-10704-7.

[14] Australian Government, *Defence Science and Technology Strategic Plan 2013-2018*, 2016, Online: https://www.dst.defence.gov.au/sites/default/files/basic_pages/documents/TRL%20Explanations_1.pdf, (accessed 5 MAR 2018)

[15] Burks, B.L., Killough, S.M. and Thompson, D.H. “Remote excavation using the telerobotic small emplacement excavator”. *Proc. of 1992 Winter Meeting of the American Nuclear Society*, pages 559-560, 1992. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/24/064/24064147.pdf?r=1

[16] Ohmori, Y. and Mano, M. “The tele-earthwork system best adaptable to remote operated construction equipment,” In *Proceedings of the 12th Intl. Symp. on Auto. and Rob. in Const.* (ISARC’95), pages 571-578, Warsaw, Poland, 1995.

[17] Hasunuma, H., Nakashima, K., Kobayashi, M., Mifune,

F. and Yanagihara, Y. “A tele-operated humanoid robot drives a backhoe,” in *Proc. IEEE Int. Conf. on Robotics and Automation*, Taipei, Taiwan, 2003. Doi 10.1109/IROS.2003.1248794

[18] Yamada, H., Kato, H. and Muto, T. “Master-slave control for construction robot,” *Journal of Robotics and Mechatronics*, 15(1): 54-60, 2003. Doi 10.1080/14399776.2012.10781052

[19] Yamada, H., Ming-de, G. and Dingxuan, Z. “Master-slave control for construction robot teleoperation - Application of a velocity control with a force feedback model,” *Journal of Robotics and Mechatronics*, 19(1): 60-67, 2007. Doi 10.1080/14399776.2012.10781052

[20] Yusof, A. A., Kawamura, T. and Yamada, H. “Evaluation of construction robot telegrasping force perception using visual, auditory and force feedback integration,” *Journal of Robotics and Mechatronics*, 24(6): 949-957, 2012. Doi 10.20965/jrm.2012.p0949

[21] Yamada, H., Xinxing, T., Tao, N., Dingxuan, Z. and Yusof, A. “Teleoperation construction robot control system with virtual reality,” *Robot Control*, 9(1): 24-30, 2010. Doi 10.3182/20090909-4-JP-2010.00108

[22] Kim, D., Kim, J., Lee, K., Park, C., Song, J. and Kang, D. “Excavator teleoperation system using a human arm,” *Automation in Construction*, 18(2): 173-182, 2008. Doi 10.1016/j.autcon.2008.07.002

[23] Sasaki, T. and Kawashima, K. “Remote control of a backhoe at construction site with a pneumatic robot system,” *Automation in Construction*, 17(8): 907-914, 2008. Doi 10.1016/j.autcon.2008.02.004

[24] Yusof, A. A., Saadun, M. N., Nor, M. K., Ibrahim, M. Q. and Hanafi, M. Z. “Position control analysis and operational evaluation of teleoperated electro-hydraulic actuator (T-EHA),” in *International Integrated Engineering Summit*, Malaysia, 2014. Doi 10.4028/www.scientific.net/AMM.773-774.163

[25] Egawa, E., Kawamura, K., Ikuta, M. and Euchi, T. “Use of construction machinery in earthquake recovery work,” *Hitachi Review*, 52(2): 136-141, 2013. http://www.hitachi.com/rev/pdf/2013/r2013_02_108.pdf

[26] Whittaker, W. L. and Motazed, B. “Evolution of a Robotic Excavator,” in *Proc. 3rd Int. Symp. Automation and Robotics in Construction* (ISARC), Marseille, France, 1985. Doi 10.1007/978-1-4684-7404-6_23

[27] Vähä, P.K. and Skibniewski, M.J. “Dynamic model of excavator,” *J. Aerospace Engineering*, 6(2): 763-768, 1993. Doi 10.1061/(ASCE)0893-1321(1993)6:2(148)

[28] Koivo, A., Ramos, M. and Thoma, M. “Dynamic model for excavators (and backhoes),” In *IFAC Proceedings Volumes*, 27(14): 763-768, 1994. Doi 10.1016/S1474-6670(17)47394-0

[29] Le, Q. H., Jeong, Y. M., Nguyen, C. T. and Yang, S. Y. “Development of a Virtual Excavator using SimMechanics and SimHydraulic,” *Journal of The Korean Society for Fluid Power & Construction Equipments*, 10(1): 29-36, 2013. Doi 10.7839/ksfc.2013.10.1.029

[30] Zhou, J., Shen, X. and Tu, Q. “Modeling of operation function of the unmanned excavator in the deterministic surfacing process,” *Applied Mechanics and Material*, 741: 526-530, 2015.
Doi 10.4028/www.scientific.net/AMM.741.526

[31] Bradley, D. A., Seward, D. W., Bracewell, R. H., Chaplin, R. V. and Widden, M. B. “Control and Operational Strategies for Automatic Excavation,” in *Proc. 6th International Symposium on Automation and Robotics in Construction* (ISARC), San Francisco, USA, 1989. Doi 10.22260/ISARC1989/0030

[32] Bernold, L. “Experimental Studies on Mechanics of Lunar Excavation,” *J. Aerospace Engineering*, 4(1): 9-22, 1991. Doi 10.1061/(ASCE)0893-1321(1991)4:1(9)

[33] Bradley, D. A., Seward, D. W., Mann J. E. and Goodwin, M. R. “Artificial intelligence in the control and operation of construction plant - the autonomous robot excavator,” *Automation in Construction*, 2(3): 217-228, 1993. Doi 10.1016/0926-5805(93)90042-V

[34] Malaguti, F. “Variable Structure Control in Excavator Robot,” in *Proc. 11th Int. Symposium on Automation and Robotics in Construction*, 1994, pp. 263-267. Doi 10.1016/B978-0-444-82044-0.50039-4

[35] Ha, Q. P., Nguyen, Q. H., Rye, D. C. and Durrant-Whyte, H. F. “Force and position control for electrohydraulic systems of a robotic excavator,” in *Proc. 16th International Symposium on Automation and Robotics in Construction*, UC3M, 1999, pp. 483-489. Doi 10.1109/CDC.2001.914787

[36] Ha, Q.P., Nguyen, Q., Rye, D. and Durrant-Whyte, H. “Impedance control of a hydraulically actuated robotic excavator,” *Automation in Construction*, 9(5-6): 421–435, 2000. Doi 10.1016/S0926-5805(00)00056-X

[37] Tazafoli, S., Salcudean, S. E., Hashtrudi-Zaad, K. and Lawrence, P. D. “Impedance Control of a Teleoperated Excavator,” *IEEE Transactions on Control Systems Technology*, 10(3): 355-367, 2002. Doi 10.1109/87.998021

[38] Immonen, M., Heikkilä, R. and Makkonen, T. “Suitability of a Three-Axis Inclinometer to the Automated Blade Control System of Excavator,” in *Proc. 32nd International Symposium on Automation and Robotics in Construction* (ISARC), Oulu, Finland, 2015. Doi 10.22260/ISARC2015/0088

[39] Lee, S.-U. and Chang, P. H. “Control of a heavy-duty robotic excavator using time delay control with integral sliding surface,” *Control Engineering Practice*, 10(7): 697-711, 2002. Doi 10.1109/ROBOT.2001.933234

[40] Choi, J. “Development of Time Varying Sliding Mode Controller with Fuzzy System for Automatic Excavator,” in *Proc. 28th Int. Symposium on Automation and Robotics in Construction* (ISARC), Seoul, Korea, 2011. Doi 10.22260/ISARC2011/0234

[41] Budny, E. and Chlosta, M. “An open-loop vs. closed-loop backhoe excavator control system,” in *Proc. 23rd International Symposium on Automation and Robotics in Construction* (ISARC), Tokyo, Japan, 2006.

[42] Matsuike, T., Sawa, Y., Ohashi, A., Sotozono, S., Fukagawa, R. and Muro, T. “Development of Automatic System for Diaphragm-Wall Excavator,” in *Proc. 13th International Symposium on Automation and Robotics in Construction* (ISARC), Tokyo, Japan, 1996. Doi 10.22260/ISARC1996/0036

[43] Ha, Q.P. and Rye, D.C. "A control architecture for robotic excavation," *Computer-Aided Civil Engineering and Infrastructure*, 19: 28-41, 2004. Doi 10.1111/j.1467-8667.2004.00335.x

[44] Maeda, G. J. "*Learning and Reacting with Inaccurate Prediction: Applications to Autonomous Excavation*," PhD thesis, University of Sydney, Sydney, 2013.

[45] Singh, S. "Learning to predict resistive forces during robotic excavation," in *Proc. 1995 IEEE Int.Conference on Robotics and Automation*, Nagoya, Japan, 1995. Doi 10.1109/ROBOT.1995.526025

[46] Tan, C. P., Zweiri, Y. H., Althoefer, K. and Seneviratne, L. D. "Online soil parameter estimation scheme based on Newton-Raphson method for autonomous excavation," *IEEE/ASME Transactions on Mechatronics*, 10(2): 221-229, 2005. Doi 10.1109/TMECH.2005.844706

[47] Towarek, Z. "Dynamics of a single-bucket excavator on a deformable soil foundation during the digging of ground," *Int. J. of Mechanical Sciences*, 45(6-7): 1053-1076, 2003. Doi 10.1016/j.ijmecsci.2003.09.004

[48] Singh, S. and Cannon, H. "Multi-resolution planning for earthmoving". In *Proceedings of IEEE Intl. Conf. on Rob. and Auto.* (ICRA'98), Leuven, 1998. Doi 10.1109/ROBOT.1998.676332

[49] Shi, X., Wang, F.Y. and Lever, P. "Experimental results of robotic excavation using fuzzy behavior control". *Control Engineering Practice*, 4(2): 145-152, 1996. Doi 10.1016/0967-0661(95)00220-0

[50] Cannon, H. and Singh, S. "Models for Automated Earthmoving," in Experimental Robotics VI, *Lecture Notes in Control and Information Sciences*, London, Springer, 2000. Doi 10.1007/BFb0119395

[51] Moghaddam, R. Y., Kotchon, A. and Lipsett, M. "Method and apparatus for on-line estimation of soil parameters during excavation," *Journal of Terramechanics*, 49(3–4): 173-181, 2012. Doi 10.1016/j.jterra.2012.05.002

[52] Vähä, P., Heikkilä, T., Kilpeläinen, P., Järviluoma, M. and Gambao, E. "Extending automation of building construction — Survey on potential sensor technologies and robotic applications," *Automation in Construction*, 36: 168-178, 2013. Doi 10.1016/j.autcon.2013.08.002

[53] Stenz, A., Bares, J., Singh, S. and Rowe, P. "A robotic excavator for autonomous Truck Loading," *Autonomous Robots*, 7(2): 175-186, 1999. Doi 10.1023/A:1008914201877

[54] Zweiri, Y. H. "Identification schemes for unmanned excavator arm parameters," *Int. J. Automation & Computing*, 5(2): 185-192, 2008. Doi 10.1007/s11633-008-0185-x

[55] Tochizawa, M., Takeda, S., Kamada, S., Hirosawa, K., Kikuchi, Y. , Wada, T. and Itoh, S. "Automatic Excavator," in *Proc. 8th Int. Symposium on Automation and Robotics in Construction* (ISARC), Stuttgart, Germany, 1991. Doi 10.22260/ISARC1991/0028

[56] Saeedi, P., Lawrence, P., Lowe, D., Jacobsen, P., Kusalovic, D., Ardron, K. and Sorensen, P. "An autonomous excavator with vision-based track-slippage control," *IEEE Transactions on Control Systems Technology*, 13(1): 67-84, 2005. Doi 10.1109/TCST.2004.838551

[57] Yamamoto, H., Moteki, M., Shao, H. and Ootuki, T. "Development of Autonomous Excavation Technology for Hydraulic Excavators," in *Proc. ICROS-SICE International Joint Conference*, Fukuoka, Japan, 2009. ieeexplore.ieee.org/document/5335241/

[58] Chen, W., Hosoda, K., Menegatti, E., Shimizu, M. and Wang, H. (Ed.) *Intelligent Autonomous Systems 14:*, Springer 2017. ISBN 978-3-319-48036-7

[59] Muro, T. "An Optimum Operation of a Bulldozer Running on a Weak Terrain," in *Proc. 5th Int. Symposium on Automation and Robotics in Construction* (ISARC), Tokyo, Japan, 1988. Doi 10.1016/0022-4898(91)90037-7

[60] Olsen, S. G. and Bone, G. M. "Modelling of robotic bulldozing operations for autonomous control," in *Proc. 24th Canadian Conference on Electrical and Computer Engineering* (CCECE), Niagara Falls, ON, Canada, 2011. Doi 10.1109/CCECE.2011.6030650

[61] Bulgakov, A., Bock, T. and Tokmakov, G. "Bulldozer as a Mechatronics System with the Intelligent Control," in *Proc. 31st Int. Symposium on Automation and Robotics in Construction* (ISARC), Sydney, Australia, 2014. pp. 768-777, 10.22260/ISARC2014/0104

[62] Ito, N. "Bulldozer blade control," Journal of *Terramechanics*, 28: 65-78, 1991. Doi 10.1016/0022-4898(91)90007-S

[63] Wang, H., Song, Q., Zeng P., and Zhao, P. "Research on control strategy for Engine of Hybrid Tracked Bulldozer," in *Proc. 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific* (ITEC Asia-Pacific), Beijing, China , 2014. Doi 10.1109/ITEC-AP.2014.6940977

[64] Peurifoy, R. L., Schexnayder, G. J. and Shapira, A. *Construction Planning, Equipment and Methods*, 7th Ed., McGraw-Hill Higher Education, 2006. ISBN 978-0073401126

[65] Tsuji, T., Nakagawa, Y., Matsumoto, N., Kadono, Y., Takayama, T. and Tanaka, T. "3-D DEM simulation of cohesive soil-pushing behavior by bulldozer blade," *Journal of Terramechanics*, 49: 37-47, 2012. Doi 10.1016/j.jterra.2011.11.003

[66] Shmulevich, I., Asaf, Z. and Rubinstein, D. "Interaction between soil and a wide cutting blade using the discrete element method," *Soil and Tillage Research*, 97: 37-50, 2007. Doi 10.1016/j.still.2007.08.009

[67] Karmakar, S. and Kushwaha, R. L. "Dynamic modeling of soil--tool interaction: an overview from a fluid flow perspective," *Journal of Terramechanics*, 43: 411-425, 2006. Doi 10.1016/j.jterra.2005.05.001

[68] Armin, A., Fotouhi, R. and Szyszkowski, W. "On the FE modeling of soil--blade interaction in tillage operations," *Finite elements in analysis and design*, 92: 1-11, 2014. Doi 10.1016/j.finel.2014.07.004

[69] Bentaher, H., Ibrahmi, A., Hamza, E., Hbaieb, M., Kantchev, G., Maalej, A. and Arnold, W. "Finite element simulation of moldboard--soil interaction," *Soil and Tillage Research*, 134: 11-16, 2013. Doi 10.1016/j.still.2013.07.002

[70] Yaojuan, Z., Kai, C., Peng, Z. and Zhilin, W. "Research on the simulation of the driving system of crawler bulldozer," in *Proc. Int. Conf. Transportation, Mechanical, and Electrical Engineering* (TMEE), 2011. Doi 10.1109/TMEE.2011.6199299

[71] Sun, D. I., Kim, S. H., Lee, Y. S., Lee, S. K. and Han, C. S. "Pose and Position Estimation of Dozer Blade in 3-dimensional by Integration of IMU with Two RTK GPSs," in ISARC. *Proc. Int Symp. on Automation and Robotics in Construction*, 2017. Doi

10.22260/ISARC2017/0137

[72] Brooks, R. A., Maes, P., Mataric, M. J. and More, G. “Lunar base construction robots,” in Intelligent Robots and Systems' 90.'Towards a New Frontier of Applications', *Proceedings. IROS'90. IEEE International Workshop on*, 1990. Doi 10.1109/IROS.1990.262415

[73] Moteki, M., Fujino, K., Ohtsuki, T. and Hashimoto, T. “Research on visual point of operator in remote control of construction machinery,” *Age*, 62: 41, 2010. Doi 10.22260/ISARC2011/0096

[74] ASI Robotics, “About Robotic Dozers from ASI,” Online: https://www.asirobots.com/mining/dozer/. (accessed 15 Jan 2018)

[75] Hemami, A. "Motion trajectory study in the scooping operation of an LHD loader," *IEEE Transactions on Industry Application*, 30(5): 1333-1338, 1992. Doi 10.1109/28.315248

[76] Worley, M. D. and Saponara, V. L. “A simplified dynamic model for front-end loader design,” *Proc. of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 222: 2231-2249, 2008. Doi 10.1243/09544062JMES688

[77] Tang, S., Yuan, S., Hu, J., Li, X., Zhou, J. and Guo, J. “Modeling of steady-state performance of skid-steering for high-speed tracked vehicles,” *Journal of Terramechanics*, 73: 25-35, 2017. Doi 10.1016/j.jterra.2017.06.003

[78] Ordonez, C., Gupta, N., Reese, B., Seegmiller, N., Kelly, A. and Collins Jr, E. G. “Learning of skid-steered kinematic and dynamic models for motion planning,” *Robotics and Autonomous Systems*, 95: 207-221, 2017. Doi 10.1016/j.robot.2017.05.014

[79] Lever, P. J. A., “An Automated Digging Control System for a wheel loader,” *Robotica*, 19(5): 497-511, 2001. https://doi.org/10.1017/S0263574701003435

[80] Grayson, W. “Autonomous Track Loader performs low-level excavation, grading tasks to boost jobsite productivity,” *Equipment World*, 19 Dec 2017. Online: https://www.equipmentworld.com/built-robotics-autonomous-track-loader/, (accessed: 15 JAN 2018)

[81] Fales, R. and Kelkar, A. “Robust control design for a wheel loader using and feedback linearization based methods,” *ISA Transactions*, 48(3): 312-320, 2009. Doi 10.1109/ACC.2005.1470669

[82] Altin, E. “Volvo Construction Equipment Reveals prototype autonomous machines,” Online: http://www.volvoce.com/-/media/volvoce/global/global-site/our-offer/brochures/volvo-construction-equipment-reveals-prototype-autonomous-machines-final-16-09.pdf?v=bE4yPw, (accessed 5 FEB 2018)

[83] Levy, A. “CNBC,” Built Robotics, 19 10 2017. Online: https://www.cnbc.com/2017/10/18/built-robotics-raises-15-million-from-nea-for-autonomous-construction.html, (accessed: 14 JAN 2018)

[84] Najjaran, H. and Goldenberg, A.A. "Landmine detection using an autonomous terrain-scanning robot,” *Industrial Robot*, 32(3): 240-247, 2005, Doi 10.1108/01439910510593938

[85] Wetzel, J. P., Schultz, G. M., Midura, M. G. and Taylor, J.-M. "Modular Robotic Control System for Landmine Detection." *Proc. of the 6th Annual Intelligent Vehicle Systems Symposium & Exhibition*, Michigan, 2006. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.510.6182&rep=rep1&type=pdf

[86] Theisen, B. and Richardson. P. "Construction engineering robot kit: warfighter experiment." *Intelligent Robots and Computer Vision XXVI: Algorithms and Techniques. Vol. 7252.* 2009. Doi 10.1117/12.805995

[87] US Military Bases, “FOB Delaram Marine Corps Base in Delaram, Afghanistan,” *Military Bases.* Online: https://militarybases.com/overseas/afghanistan/fob-delaram/, (accessed 15 JAN 2018)

[88] Holloway, J., “British Army takes remote-control of Terrier, the digging-est dog of war,” https://newatlas.com/bae-systems-terrier/27819/ (accessed 17 FEB 2018)

[89] Lavery, K., “Convoy of Connectivity: U.S. Army Tests Autonomous Trucks in Michigan,” *WKAR*, 8 Nov 2016. Online: http://wkar.org/post/convoy-connectivity-us-army-tests-autonomous-trucks-michigan#stream/0, (accessed 5 MAR 2018)

[90] Israeli MOD. “Israeli Army Introduces Unmanned Bulldozers,” Defence Talk, 27 Sep 2011. Online: https://www.defencetalk.com/israeli-army-introduces-unmanned-bulldozers-37260/, (accessed 25 FEB 2018).

[91] Ha, Q., Santos, M., Nguyen, Q., Rye, D., and Durrant-Whyte, H., “Robotic excavation in construction automation,” *IEEE Robotics & Automation Magazine*, 9(1): 20-28, 2002. Doi: 10.1109/100.993151.

[92] Singh, S., “The State of the Art in Automation of Earthmoving,” *Journal of Aerospace Engineering*, 10(4): 179-188. Doi: 10.1061/(ASCE)0893-1321

[93] Su, S., Rudas, I., Zurada, J., Er, M., Chou, J. and Kwon, D. “Industry 4.0: A Special Section in IEEE Access,” *IEEE Access*, 5: 12257 – 12261, 2017. Doi 10.1109/ACCESS.2017.2704758

[94] Jones, K. “Entering The Age of Self-Driving Construction Equipment,” Online: https://www.constructconnect.com/blog/construction-technology/entering-age-self-driving-construction-equipment, (accessed: 15 FEB 2018)

[95] Ha, Q.P., Tran, T.H., Scheding, S., Dissanayake, G. and Durrant-Whyte, H. “Control Issues of an Autonomous Vehicle”, *Proc. 22nd International Symposium on Automation and Robotics in Construction* (ISARC), Ferrara Italy, September 11-14, 2005. http://www.irbnet.de/daten/iconda/CIB13796.pdf

[96] Voth, D. “A new generation of military robots,” *IEEE Intelligent Systems*, pp. 2-3, Jul-Aug 2014. Doi 10.1109/MIS.2004.30

[97] Cook, J. T., Ray, L. E., and Lever, J. H., "Dynamics modeling and robotic-assist, leader-follower control of tractor convoys," *Journal of Terramechanics*, 75: 57-72, 2018. Doi 10.1016/j.jterra.2017.05.002.

[98] Tran, T. and Ha, Q. *Quadratic Constraint Approach to Model Predictive Control of Interconnected Systems*, Springer, ISBN 978-981-10-8407-2, 2018.

[99] Alur, R., *Principles of Cyber-Physical Systems*, MIT Press, ISBN: 9780262029117, 2015.

[100] Johnson, R., Ground Robotics Capabilities Conference, “https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2009/groundrobot/Johnson.pdf, (Accessed 5 FEB 2018).