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 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 military 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 technical feasibility, maturity, 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 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 automating construction processes by applying the principles of industrial automation [1-3]. Among general construction processes, there have been resurgent interests in automation of earthmoving equipment such as wheel loaders and bulldozers in a framework of modelling, control, planning and artificial intelligence with the use of sensing and information technologies [4,5] in the framework of robotic and autonomous systems (RAS) applied to construction automation [6]. To this end, a great deal of effort in research and development has been devoted to raise the level of autonomy, in both civilian or military domains, to improve their efficiency, productivity, quality and reliability [7].

Robotic systems used in military applications represent RAS that integrate sensors, vision imaging, actuators, end-effector manipulation, computer control and human interface, operating in hard, heavy and hazardous conditions. In army operations, construction tasks required to enhance the force and the force protection usually include such earthmoving tasks as filling of protective barriers (HESCO baskets), building retaining walls around storage using dirt (dirt bunding), as well as anti-tank ditching and trenching. For this, a variety of heavy construction machinery such as excavators, bulldozers, wheel loaders, graders, rigid frame trucks, articulated dump trucks, backhoe loaders, rollers, pavers, all-terrain fork lifts, etc. were developed with custom designs to meet the military's special needs.

As military engineers nowadays are almost entirely engaged in war logistics and preparedness, higher demand in terms of both protection and efficiency are becoming prevalent requiring the transformation of those equipment to semi- or fully autonomous systems. Studies in this field therefore have recently received much research interests. In [8,9], surveys of RAS used in military applications have been conducted with discussion on unmanned ground vehicles (UGV) and air/sea robotic vehicles. However, the focus therein is mainly on combat and logistic operations rather than construction. Given 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], this brief survey aims to provide a comprehensive overview and analysis on the state-of-the-art of earthmoving construction automation used for army applications. The objectives will cover construction tasks and corresponding platforms in alignment with defence applications. These include excavators, bulldozers and wheel loaders in tele-operated, share-controlled, semi-autonomous, or autonomous execution.

As majority of military operations are coordinated, networked robotics and collaborative automation have offered an excellent solution to the problem of coordination via applications of either teleoperated robots with human interaction or multi-robot systems.

These are deployed to cooperatively perform a task by exchanging sensing data and information via the communication network, where sensing, control, planning and memory data flow within layers of the Internet of Things [11, 12].

2 RAS in Ground-Based Construction – A Review

The RAS application to typical platforms such as excavators, bulldozers and wheel loaders is evaluated via studies in teleoperation and autonomous operations [13] on the grounds of the technology readiness level (TRL) scaled up to 9 levels [14], from basic principles (TRL 1) to commercial deployment (TRL 9).

2.1 Excavator

2.1.1 Remote control and Teleoperation

In remote control and teleoperation, the focus is to develop reliable human-machine interaction model and real-time data feedback. One of the earliest studies in this direction is conducted in the early 1990's by Burks *et al.* [15] in a study funded by the U.S. army with the aims to find principles for teleoperating excavators and use them in retrieving unexploded ordnance or 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 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 slow grasping of a soft object by improving the sense of grasping through force feedback application [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, confirming 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 being tested by using 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, known as PARM, which can replace a human operator [23]. The effectiveness of the remote-controlled operations conducted at local construction sites has been determined by the increase in working efficiency of more than 50% compared to the direct operation of the excavator. The same concept was studied by Yusof *et al.* (2014) 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 restoration [25], which marked the RAS application in large-scale unmanned construction of post disaster recovery works.

2.1.2 Autonomous Excavation

Study in autonomous excavation started in 1986 at CMU in which a prototype named Robotic Excavator (REX) was developed [26]. REX 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. Theexcavator 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 formulation in 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 regarded as a planar manipulator with three degrees of freedom (boom, dipper and bucket) are derived using the Lagrangian formulation. A virtual model for excavators was developed for an earthwork site, whose terrain geometry is continuously updated as excavation and earth-moving continue until completion, 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 TRL 3-6, 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 the 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 was implemented in a Komatsu 1.5-tonne excavator demonstrated that the proposed control technique can provide robust performance when employed in autonomous excavation with soil contact considerations. The impedance control was also discussed later in [37] for a tele-operated excavator. 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 PD-type sliding surface. The proposed controller was applied to linear motion of the whole excavator at the same speed level as that of a skilful human operator. In [40], the time-varying sliding mode controller (TVSMC) combined with fuzzy algorithm has been used for an unmanned excavator system. The computer control system [41] was implemented in 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 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 arisen in 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 nonmonotonic transients and converged faster by learning disturbances directly from command discrepancies.

Interactions between construction tools and the soil represent are 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 large computational time and hence are infeasible for application in 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 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 more computationally-effective than the FEE. After all, soil behaviour by 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 7-8 a pioneer system was demonstrated by Stenz *et al*. (1999) [53]. The system is the first fully autonomous loading system for excavators which are 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 drain. This system was composed of two sub-systems, an automatic surface finishing system and a laser guide systemfor excavating ditches up to 8 km. 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 vehicle from a starting position to a goal position. A prototype of 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 for the crawler dump truck. More recently, a prototype system which is based on a Volvo EW 180B excavator has been reported as part of the autonomous excavator project THOR (Terraforming Heavy Outdoor Robot) that its goal is the development of 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, pioneer work on autonomous bulldozers started several decades ago, similarly to excavators. Muro (1988) introduced an automatically controlled system for maximising productivity of a bulldozer running on a weak terrain [59], whereby a microcomputer was used to obtain information of terrain properties and vehicle states so that based on those information, optimum drawbar-pull and slip ratio could be computed during digging. Since then, various studies have been conducted, focusing on different relevant research topics such as modelling and control, position and pose estimation, machine-soil interaction, navigation, simulation, teleoperation and pilot and real 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 resistance strain of gauge bogie displacement on the dig depth and trolley speed in dynamics. The force acting on the blade was first modelled and a model-based adaptive control strategy was then proposed to control the blade. The control of bulldozer blade could be addressed by using the fuzzy theory for in a semi-automatic control 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 its fuel consumption.

In the soil cutting and pushing process, the blade experiences the 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 experimentally [65] or using numerical methods [66], whereby a cohesive bond force model was introduced in which the microscopic behaviour of 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 also conducted with the finite element method for soil mechanics and the failure zone using various models like constitutive equations of soil failure [68] and 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 also the driving force. The results provided a reference for improving performance of the crawler bulldozer drive system [70]. Recently, a guidance system for bulldozer has been developed using sensor fusion. The integration of an inertial measurement unit (IMU) with two RTK global positioning systems (GPS) allowed to accurately estimate the pose and position of the bulldozer blade, providing feedback for the navigation system [71]. Experiments on a full-scale bulldozer were implemented to verify the validity of 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 operation against of a disaster occasion. Most 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. 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 shapes, sizes, and applications.

2.3 Loader

Autonomous loaders are considered as an integrated system of hydraulic, mechanic and electronic subsystems. Being widely used at construction sites, these machines have received much research interest to continuously improve its 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 motion with the ability to store and recall trajectories. Since then, a number of studies have been conducted to model loaders, which are essential for improving their performance and autonomy 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 based on classic 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 filtering 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 via experiments on a large Caterpillar wheel loader model 990, as reported in [80]. In another approach, an H-inf 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 the level 7-8 for integrated systems, Volvo Construction Equipment developed its prototype of fully autonomous haul truck and wheel loader and demonstrated it in 2016 [82]. Most recently, a fully autonomous track loader has been developed and tested in field work by Built Robotics Inc. taking advantages of the dramatic advances in the self-driving car technology. The developed software and sensors can turn off-the-shelf loaders and excavators into robots that can do earthmoving tasks with precision 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) which is a ruggedized military vehicle with backhoe and front loader used by the U.S. Army for explosive ordnance disposal (EOD), combat engineer, and general utility excavation activities. Its features included 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 could autonomously manipulate a typical handheld detector for remote sensing of buried landmines using map building and path planning implemented into a real-time software. A commercial Modular Robotic Control System (MRCS) was first integrated into 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 like excavating, digging, lifting/loading, stripping, levelling, and stockpiling.

Apart from MRCS, another common-off-the-self robotic kit, the Appliqué Robotics Kit (ARK), was also designed to allow the modification of existing plant equipment to remote control with the minimum of host vehicle modification and with little invasion of 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 the operational use and supported hasty route clearance operations for military purposes. These unmanned ground vehicles can also be used for other purposes such as surveillance, remote monitoring, engineer, military police, 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 in use for centuries as a means to help defend military operations. This could be in the form of moats, foxholes, or other bunkers to protect equipment and force. 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 additional protection requires additional time and is rarely a form adapted in actual battle conditions. Other forms of military earthwork are moats, which are quite often built around inhabited areas and then filled with water to slow down any enemy onslaught. Modern day warfare uses the same technology in creating tank trenches quite often for miles together to slow down any armoured column assault.

A *forward operating base* (FOB) is any secured forward military position, commonly a military base, that is used to support tactical operations. An 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. An FOB also improves reaction time to local areas as opposed to having all troops on 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, or ECP. 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 illustrates a FOB, located along the 2,000 km in Afghanistan's Delaram District, built by the US Marine Corps with the help of an excavator [87].

Fig. 3: Building Delaram FOB [87]

A common example of military earthwork is to put in place a *barrier* between the army and the enemy for force protection. The basic form of any such earthwork operation is a mound of earth or embankment that rises above the general ground level. This embankment is formed from earth that is excavated in the same area forming a ditch. This ditch also adds to the height or depth available for protection. The *foxhole* is the simplest form of military earthwork normally dug in position by the soldier who is going to use it for his defence in an actual battle. A section of soldiers may connect up their individual foxholes to make a continuous trench that can also be used to facilitate the supply of ammunition and communication with commanders.

The *HESCO bastion* is a modern gabion primarily used for flood control and military fortification. It is made of a collapsible wire mesh container and heavy-duty fabric liner, to be used as a temporary to semi-permanent levee or blast wall against explosions or small-arms. HESCO is commonly used in FOB wall constructions. One of the best features of the HESCO is the ease in which it is set up. Get the dirt or content flown in or pull it off a truck, unfold it, use a front-end loader or other heavy-duty equipment to fill it up with dirt, sand or gravel within a short time for setting up. One soldier operating a front-end loader and four more unfolding the shells can set up a wall in just couple of hours. They can essentially work ten times faster than crews filling sandbags.

In an open site, *antitank ditches* are constructed to strengthen prepared defensive positions. As they are costly in time and effort, 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. 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 space on the friendly side nearly vertical by means of hand tools. 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 the first Terrier combat teleoperated drive-by-wire vehicle by The British Army. The armored tracked vehicle, made by BAE Systems, is equipped with a hydraulic front bucket and an excavating arm such that it can be remotely controlled not only to clear routes or create cover, but also to dig trenches for troops on the ground, or to hollow out anti-tank ditches [88]. It is believed the technology can assist operators in digging anti-tank ditches, turret and hall defilade fighting positions in harsh conditions.

Fig. 4. Teleoperated trench digging [88].

3.3 Military use of earthmoving machinery.

The RAS application has been widely used in the army. The Australian Defence Force (ADF) has fielded the protected High Mobility Engineer Excavator (HMEE) to repair damaged routes and create bypass routes. The HMEE, shown in Fig. 5, is an ADF self-deployable excavation system with attachments to execute a wide range of mobility, counter mobility, survivability and counter-improvised explosive device (CIED) missions [89].

Fig. 5. ADF self-deployable excavation system [89].

For military use, bulldozer blades can optionally be fitted on other vehicles, 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 firearms and debris, enabling bulldozers to operate in combat zones. The Engineering Corps of the Israeli Army has 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, detonating explosive charges [90]. Front loaders are also commonly used in military applications for building or removing road blocks and building bases and fortifications. Since 2005, they have also been used to demolish small houses. Armour plating was added to the loader to protect it against rocks, stones, molotov cocktails, and light gunfire.

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

4 Construction Automation - A Projection with military applications

Since the last decade of the 20th century with convincing evidence of robotic excavation in construction automation [91, 92], the enabling technologies of RAS from the academic research and industrial development for the autonomous execution of construction tasks using ground-based platforms such as excavators, dozers and loaders have become quite mature and ready for the next stage of development into commercial-off-the-shelf products. In addition, embracing the recent advances in manufacturing with Industrie 4.0 (see, eg., [93]), cloud computing, and cyber-physical systems and the Internet of Things, tomorrow's technologies for construction automation can be foreseen in the improvement of site efficiency with a plethora of CAD and building information system; data mining; connected devices including sensors or smart devices; building prefabrication; collaborative delivery of services and goods; autonomous systems ranging from autonomous earthmoving platforms through to drones; sensing technology, especially in the management of health and onsite safety; cloud computing and mobile friendly; mobile apps; virtual reality design; holographic headsets; thermal imaging and low-energy and low carbon structures for green and sustainable construction; exoskeletons for construction; engineered living materials; and new technology trends such as remote surveillance, wearables, 3-D printing, digital documentation, mobile field service software, and connected driverless vehicles. Looking ahead at the use of RAS in construction, Kendall Jones, the Editor-in-Chief of the ConstructConnect blog [94], emphasises on the efficiency and accuracy, envisaging an automated construction site in the future will have a fleet of bulldozers, graders, and excavators doing site preparations without any operators behind the cabin controls, some having no cabins.

In defence, dated back in WWII of the last century, when the U.S. and Germany started to develop unmanned air vehicles (UAVs) for warfare purposes, military robotics has made tremendous progress. 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 different missions including Explosive Ordnance Disposal (EOD), Combat Engineering, Reconnaissance, and other Civil works. Robotics and automation systems, including unmanned ground, aerial, underwater, amphibious vehicles [95], anti-munition systems, armed robots, cyber-attack and -defence systems are projected to become a centrepiece of military operations in the years ahead. Randall Steeb, a senior scientist at Rand Corporation, commenting on the US Army's Future Combat Systems program, emphasised on autonomous, armed cooperative robots [96]. Cooperation of unmanned vehicles with humans and machines in construction has been attracting the robotics and automation community in addition to the wide-spread used concept of teaming in military 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]. This view together with the emergence of collaborative intelligent manufacturing are substantiated by efficient and adaptive RAS equipped with communication networks that can simultaneously meet the expectations of ever changing operation environments and recover from disturbances.

In construction and infrastructure, the emerging field of the Internet of Things (IoT) are directly applicable to the technologies for interconnected systems, consisting of several communication layers, e.g. 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

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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).

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 the application of intelligence science, data science and Internet of Things (IoT) or cyber-physical systems. In military domain, IoT finds direct applications in such operations that are often conducted in a complex, multidimensional, highly dynamic and disruptive environment, e.g. a FOB, where commanders have to accurately and promptly assess the situation, to gather all possible sources to obtain the most complete and relevant picture in order to make decisions. Scenarios for use of IoT in warfare conditions may include its applications to support tactical reconnaissance, or 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 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, interoperability and integration of disparate technologies.

5 Conclusion

We have comprehensively surveyed the use of RAS in earthmoving construction machinery with applications to the army. Typical automated platforms such as excavators, bulldozers and front-end loaders are reviewed in aspects of modeling, control at low and higher levels, system architecture, sensing and navigation, toil-soil interactions, simulation and experiments from laboratory set-ups to full-scale field tests, in remotely-controlled, teleoperated, semi-autonomous and autonomous operations. RAS developments on these platforms are scanned from several decades ago till the moment and evaluated in accordance with their technology readiness levels ranging from basic principles observed to actual systems proven through successful mission operations. Military applications of these platforms include explosive ordnance disposal and landmine detection, forward operating base construction, bastion filling and antitank ditch formation. Given the maturity level of the RAS technologies in ground-based construction automation towards commercial-off-the-shelf products, new trends of IoT-based automation with data exchange in manufacturing technologies, and taking into account vision from experts in the areas, a glimpse on future construction automation is included with an emphasis on ground vehicles teaming.

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