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Intelligent Robotic Systems for Military Use, from Past to Present and Beyond: A Comprehensive Review and Taxonomy

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Abstract

From the beginning of biologically inspired robots, researchers have been fascinated by the possibility of interaction between a robot and its environment, and by the possibility of robots interacting with each other. Robots may perform dangerous tasks can operate remotely of collocated in the same room as its user, are engaging, motivating, encouraging imagination and innovation, and may improve literacy and creativity. As an inevitable result of the exponential growth of robot applications in industry and in civilian service, intelligent robotic systems have been used with success in warfare. They will soon be ubiquitous, with a continuously growing variety of applications such as target detection, identification and tracking, weapon guidance, reconnaissance, autonomous

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guidance of land, sea and air vehicles, terrestrial image mapping, simulations of military equipment, battlefield training, support, etc.

Such entities are a growing industry from both a research and commercial perspective. Thus, it is desirable to present a review on intelligent robotic systems to serve as a tutorial to people inside and outside the field, and to promote discussion of a unified vision for these agents with a particular focus on military use. In particular, a comprehensive taxonomy of robots used in warfare is compiled, key points in the field are identified, and challenges are discussed that are likely to shape the specific area in the near future.

Their application on the battlefield though, raises several challenges, moral and ethical issues that are also discussed in this work.

Mathematics Subject Classification: 68T40

Keywords: Military robots, robots in warfare, combat robots, intelligent robotic systems, robot taxonomy, robot architecture.

1 Introduction

The scope of this review is to present a unified approach on intelligent robotic systems with a particular emphasis on robotic systems for military use, to compile an extended and comprehensive taxonomy of robots used in warfare, to identify and spot key points in the field as well, and discuss the challenges that are likely to shape the specific area in the near future.

2 Preliminaries

A robot is an intelligent autonomous system incorporating sensors, processors, and effectors, having several capabilities such as sensing, acting, communicating, etc. It is able to perceive parameters of the environment, make decisions and act upon these parameters.

A robot can complete tasks that are given or taught by a user. The user can be a human or in some advanced projects can be another robot as well. A robot can interact and adapt to its environment in order to successfully complete the tasks given by the user.

Since the First World War, there was a growing deployment of automated air ground and water vehicles. So far, there are a lot of robotic systems used in the warfare. They are spreading in the battlefields and the trend is to use autonomous systems instead of humans.

3 Structure of robotic systems

From a general perspective, the architecture of such a sophisticated entity can be divided into three complimentary and strongly coupled layers: the low, medium, and high level layer.

The former constitutes the physical part of the system including the hardware/software components, sensors, actuators, monitoring, estimation, filtering, communication, interaction, telemetry, autonomy modules, etc.

The medium and high level layers constitute the cyber-physical part of the system. The medium level layer may include interaction, communication, message passing, processing of data, generation of tasks capabilities, etc.

Finally, the high level layer is responsible for the cognition capabilities of the robot and may include processes related to knowledge, such as attention, memory, judgment and evaluation, reasoning, problem solving and decision making, comprehension and production of language, beliefs, desires, intentions, etc.

4 Taxonomy

Autonomous robotic systems can be classified according to different modalities. The modality impacts on the basic design and capabilities of the robot and the task concerned.

A comprehensive taxonomy has been deployed in order to classify military intelligent robotic systems based on size, mobility, endurance, mission, user properties, command-control-communication link, propulsion, altitude, level of autonomy and other functional or operational parameters as well. Groups of robotic systems have been defined on the basis of shared characteristics, and generic features of the robotic platforms have been distinguished. Taxonomy classes are described as follows:

4.1 Functional Taxonomy

On a functional basis, robotic systems are divided into two main categories: military and civilian.

4.1.1 Military robotic systems including:

-Unmanned Vehicles (UVs) which can be categorised according to three characteristics: a)Size, b)Payload capabilities, c)Endurance

-Security robotic systems,

-Training and simulation systems,

-Wearable systems (exoskeletons),

-Support robotic systems

4.1.2 Civilian

In this category robotic systems can be found in either commercial or public (civilian service) applications. There are:

-Industrial,

-Commercial / Household, (home security robots, non-intelligent robots (static), buddy robots, intelligent robots, pet robots, story telling robots, personal assistant robots, edutainment robots),

-Healthcare, (rehabilitation, therapy, robot assistants for disabled, companion robots for the elderly, conversational robots, etc),

or either Surveillance, Search and Rescue, Transportation, Payload delivery, Traffic control, Scientific research, Disaster/Emergency responce, etc.

4.2 Operational medium Taxonomy

In terms of the operational medium, military robotic systems can be classified into five categories:

4.2.1 Air medium: (UAV)

4.2.2 Ground medium (UGV)

4.2.3 Sea medium including a) Surface and b) Underwater systems

4.2.4 Space medium

4.2.5 Hybrid medium (amphibious)

Following there are classes of robotic systems provided, operating under the previously mentioned modalities with an emphasis on control and autonomy capability.

4.3 Control and autonomy Taxononomy

Most control problems deal with robustly tracking reference signals, regulation, stabilisation etc. in an autonomous manner. Nowadays the demand is towards the development of such self regulating mechanisms that may act in a real-time, robust, efficient manner and to operate for an extended period of time without the human intervention/supervision. The main key ingredients of such mechanisms that characterise a fully autonomous system are: control capability and autonomy and should be distinguished explicitly. By the former it is the ability of a dynamic system to perform specific tasks in a desired and predictive manner. By the latter, autonomy is the capability of a system to pursue or fulfil its operational objectives without human intervention. To accomplish the above, the attributes for complex autonomous systems deal with modeling of dynamically changing environments, learning various skills in feedback interaction with the environment, detecting event and actions in order to perform adequate logic based decision making, the ability to understand and explain the decision-making to humans and to transfer expert knowledge to the autonomous system. Thus research is towards defining a systematic approach to classify the levels of autonomy that may constitute a system with autonomous control capability and to formally verify/certify those.

Robotic systems in this class are divided according to control and autonomy capability features. Humanoid robots, pets and ground vehicles may have possibly higher levels for autonomy but we restrict ourselves to minimal practical requirements.

4.3.1 Remotely Controlled

This class of systems include model systems with remote control units, that offer no autonomy and are operated within a distance via specific frequency bandwidths.

4.3.2 Low level autonomy

Those that can carry out necessary tasks in an autonomous manner. These may include tracking trajectories, meeting waypoint constraints, carry out scheduled tasks such as photography, perform sensor fusion, visual analysis, etc. The requirements for the mission are that the navigation step and the mission planification are a-priori prescribed by an operator. These steps often take into account physical and functional constraints of the vehicle, fuel efficiency and obstacles. Additionally, their capabilities often involve to plan and timely execute mission related tasks such as photography or collecting samples from the environment.

Some of the ingredients for low level autonomy include good navigation system (ie. fusion of GPS, IMU, depth/altitude sensor and a sophisticated filtering mechanism), controller that is suitable for tracking, low processing memory, etc.

4.3.3 Medium level autonomy

Those that persist to successfully perform tasks against seriously adverse environmental conditions. This may involve the generation of actions and paths to meet missions objectives while in mission and/or reaching areas of interest under a dynamically changing environment. Advanced abilities involve decision making and re-planning of the mission, tasks, and path to meet the requirements which is performed using on board features. Among others, necessary requirements for medium level autonomy are, onboard re-planning algorithms, simple agent architecture such as parallel processing, reconfiguration strategies to handle sensor failures, multiple processors units, large memory, etc.

4.3.4 High level autonomy

Those that may “understand” high level tasks via subtasks and have decision making capability. These often utilise a multi-layered set of agents that may interpret high level goals and represent this into linguistic expressions to its operator for verification purposes. In particular the instructions to the autonomous vehicle are issued at the level of goal statements and the autonomous system should be able to work out a hierarchical plan system based on multi-resolution modeling of the environment under action constraints. Thus behavioural capability is formed. At high level autonomy the knowledge necessary involves, onboard knowledge of missions, operational environment constraints, physical functional constraints of the vehicle, interpret high goals in terms of a language describing the environment, ability to generate sub-goals and sub-plans to achieve higher level goal, realtime ability to re-generate plans in the event of dynamically changing conditions, large (multi-) processor capacity and memory, ability to interpret a highly abstract goal given, etc.

For humanoid robots architectures go beyond the aforementioned setup using more complex types of architectures. These may often accommodate characteristics such as, motivations, emotions, playfulness, comprehensive learning ability, social behaviour, shared knowledge development, etc. In an algorithmic perspective the architectures can be described by three different schemes of agents, respectively. At low level of autonomy there are the reactive agents (the behaviour is determined by sensed features of the environment). By the medium level there are the deliberative architectures (based on prior knowledge of the world and planning possible actions are chosen. By high level of autonomy the Beliefs, Desires, Intentions (BDI) deliberative architectures use goal setting, planning, intentions and desire generation to form the autonomous system.

Reviews of key areas in current underwater robotic technologies are presented in references [37], [34], [28], and [6]. Pertinent points and examples of control architectures used on various types of AUVs are discussed in survey [35] for the interested reader. Autonomous ground vehicles are best known from the DARPA Grand Challenges (http://www. darpa.mil/grandchallenge/index.asp) and the

DARPA Urban Challenge. The goal has been to follow a route and safely arrive to a distant location without hitting obstacles and causing damage on the way. To name a few references the reader is pointed to articles [5], [20] and [24], [8].

Levels of autonomy and certification for unmanned flying vehicles are the most developed for unmanned vehicles. UAV systems have been designed and built using various decision-making mechanisms such as hierarchical [14], [31], reactive and behavioural based [29], [36], [38], and [4].

A lot of UAV related effort has been devoted to path planning [15], fault diagnosis [12], and to navigation [3] to aid decision making. There is a large number of papers on these topics, the interested reader is referred to survey [35] for a thorough list of applications.

Autonomous vehicles operating in the space environment are becoming pivotal in the achievement of complex exploratory missions where human presence, or tele-presence, is not possible. Autonomous vehicles operating in such environment encompass a broad range of vehicle types (air, ground or water). While these applications are extensions to those observed within our terrestrial environment, autonomous vehicles in space also capture very different scenarios involving small bodies such as comets, exploration and categorization of hazardous asteroid belt environments. All of these scenarios involve an inherent need for autonomy owing to mission-critical communication delays, and communication loss. An early overview of the future possibilities for using agents in space missions is presented in reference [23].

ESA and NASA have started planning and executing technology proving missions. Perhaps the most documented and relevant of these missions is the Remote Agent (RA) experiment by NASA: an autonomous spacecraft agent used to operate the Deep Space 1 spacecraft [26]. The Automated Rendezvous Vehicle, constructed and operated by ESA. Behavioural approaches within space vehicle systems have been investigated greatly by ESA. In [22] details the design of Remote Agent, which fuses both reactive and logical agent frameworks to provide for both robust plan execution and the ability to develop plans to achieve goals.

4.3.5 Control methodologies

In this section an attempt to briefly catetogise, the different control methodologies, and the necessary tools for the design of the control law to meet objectives is included. Without loss of generality, the control problem addressed herein is that of navigation of a vehicle although the methodologies outlined can be applied to other control problems.

4.3.6 Linear control techniques

In general nonlinear systems are typically far more complicated than can be addressed by standard control techniques and are more complicated than necessary for most flight regimes, for example. Thus numerous simplifications can be applied that may prove helpful in synthesising the closed-loop system and achieving the control task concerned.

Linear control techniques are well understood, and are widely utilised due to their simplicity, ease of implementation, and associated metrics of stability and performance. The reader is pointed to book [25] for a detailed treatment of linear control theory, methodologies and design issues. For linear control techniques to be applied it is necessary to linearise the nonlinear differential equations representing the system. Thereafter the design proceeds to guarantee stability for closed-loop system using tools from linear control theory. To name a few methods that have been successfully applied to UAVs the reader is pointed to the nested loop architecture [18], state space control techniques [25], (Proportional Integral Derivative (PID) controller [7], and robust control techniques [1] in the case of modelling uncertainties and noise in sensors.

4.3.7 Nonlinear control techniques

In order to meet increasing demands on performance and reliability of unmanned robotic systems nonlinear and adaptive techniques are employed. Using these, nonlinearities, saturation effects, modeling uncertainties, inaccuracies, disturbances, noise in sensors, time varying parameters, delay, etc. can be handled effectively. There are numerous nonlinear control techniques used for unmanned vehicles and it is still an active area of research. Some of those are gain scheduling [18], model predictive control [9], backstepping [17], dynamic inversion based control [13], model reference adaptive control [2], model based fault tolerant control [11] (divided into passive and active techniques), sliding mode control [10], fuzzy control [16], reinforcement learning based methods, adaptive control [2], robust and adaptive control techniques [27], etc. In these techniques a necessary tool is Lyapunov theory [13], [32] in order to prove stability and synthesise the control law. A necessary prerequisite is the a-priori knowledge of some mathematical representation of the system under investigation.

4.3.8 Architecture of Control methodologies

Complex engineered systems, combine a diverse grouping of hardware and software technologies for their performance and effectiveness. They must incorporate in their design and operation sophisticated hybrid architectures that integrate in a rather robust way and meet stringiest performance requirements. There are three different types of architectures that can be found in applications and are often used in individual systems (or group of subsystems) or a team of vehicles. These are, centralised, decentralised, and distributed. Their advantages, disadvantages, and design issues can be found in work [19], among others.

4.4 Payload Taxonomy

Unmanned vehicles have limited payload volume and weight capacity. These limitations result in several additional constraints, to name a few, electronic components must avoid electromagnetic interference (EMI) interactions, risk increases by their close proximity, power is limited by the space and weight available for energy/fuel reserves; total payload operational time is limited by the available power; power processor speed is limited by the weight and power available, and sensor capabilities are limited by available weight allocation. Vehicle systems can be divided according to payload characteristics such as, weight, power, and volume allocation.

4.5 Size Taxonomy

Robotic vehicle systems can be broadly categorised into types based on their size. These can be described as:

-Man-packable
-Man-portable
-Maxi-sized

The size of the robot impacts both on the tasks for which it is suited for and how immediate its deployment may be. The first group involves robot systems (including the control unit, batteries, and tools) that can be carried and fitted into backpacks. These are most likely to be used almost immediately, for example after a disaster carried by responders over debris or into the core of the disaster. These may be small in size with either ground, aerial or water capability, in order to reach or infiltrate a particular section of a building, while the rest of the equipment is operated from a distance. These systems have limited capability of autonomy and functionality due to its size and battery resources. For instance, those can perform basic tasks such as map an area, navigate autonomously, take photos, etc. Additionally, man-packable aerial robotic systems can perform better if deployed in fair environmental conditions or indoor environments due to their limited propulsive capabilities. In essence, persistent conditions such as gusts of wind, may immobilise or result in poor performance of the system.

Man-portable robotic systems are larger in size from the previous category and can be carried a short distance by two people or on a small all-terrain vehicle. Those be used as accessibility within the hot zone improves or outside the hot zone for logistics support.

For the third category trailers or other special transportation logistics are required for their deployment. These may be in one piece or in parts and are often operated by a team. For example the Sperwer UAV by Sagem S.A. [33] fits into a large container, requires a special launch platform and is operated by a crew from a ground station. Its deployment (ie.assembly, launch) according to the mission scenario is fast. Their insertion into the hot zone can be made from a safe distance depending on the communication constraints. The capabilities for maxi-sized robotic systems are numerous according to the tasks/missions and payload concerned. Their autonomy capability is high since those systems often require intermittent communication capability to the ground station and can perform high level decision tasks formed by subtasks while in mission.

Other types of taxonomies based on their modality (ie. ground, aerial, water) and size, or based on their modality, size and task have been proposed by [21] and [30], respectively, for rescue robots for example.

4.6 Other Taxonomies

Other taxonomies for UxVs exist in the literature, for example these catagorise systems according to the environment considered (climbing, terrain), articulated, wheeled, hybrid, rotary, fixed wing, propulsive means, mission communications (synchronous/ asynchronous, continuous, discrete, intermittent, point to point), etc.

5 Military applications of Robotic Systems

Related to the features of the systems, some of the typical areas of application include the following: target detection, identification and tracking, weapons/missiles guidance, photo reconnaissance, analysis and screen interpretation, remote and local site monitoring, autonomous guidance of land, sea and air vehicles, terrestrial image mapping, simulations of military equipment and battlefield training.

Some applications/examples of military robotic systems are listed below:

Unmanned Ground Vehicle: Talon (Foster-Miller), XM 1219 Ground Combat Vehicle, (Lockheed Martin / Boeing).

Unmanned Air Vehicle: MQ-1 Predator UAV (General Atomics).

Unmanned Sea Vehicle: Hydra Sea Drone (DARPA), Ghost Swimmer (US Navy / Boston Engineering).

Amphibious Robot: Guard-Bot (Guard-Bot Inc).

Wearable system: XOS 2 High Power Robotic Exoskeleton (RAYTHEON).

Support Robotic System: LS3 (Boston Dynamics), Battlefield Extraction-Assist Robot -BEAR, (VECNA Technologies).

Humanoid Robot: Robo-corp Atlas (Boston Dynamics).

6 Discussion: Challenges and Limitations

The key themes identified are pertinent to robotics, with a particular emphasis on robotic systems for military use. They impose challenging issues that are likely to shape the field in the near future.

6.1 Endurance

Power sufficiency of military robots extends up to several hours depending on the energy source used. When power from batteries lasts few hours, it can last much longer on diesel motors or generators and many days as in some solar powered UAVs or energy efficient micro/nano robots.

6.2 Autonomy, control, real time capability

The level of autonomy of military robots increases steadily, and the need of a human operator is eliminated with the use of powerful sensory, onboard data processing and analysis system.

6.3 Size

There are virtually no limitations to the size of the robots used in military missions. Technology is already able to provide a span of robots, big or small as to appropriately fit to the mission assigned. There are already micro insect-shape robots and self-guided bullets or multi-ton unmanned vehicles.

6.4 Communications

Coordination through communications is critical for robotic teams, especially in battlefield. In particular, intelligent robots along with a broad range of smart devices will become multi-modal interfaces, with computers or networks of computers through Internet of Things, for a large and complex set of missions and tasks.

6.5 Safety and Security

Advanced systems are already in the battlefield and it is a matter of time for developers to achieve almost-human or even human cognition and behavior for the robots. Even at that time it will not be easy to define whether it will be safe to completely remove human intervention.

6.6 Fault tolerance, Adaptability, and Reconfigurability

Advances in fault-tolerance, adaptability and reconfigurability of military robots induce increased versatility and resilience. As well, they induce capability of acting in multiple terrains.

6.7 Decision making

The development of advanced sensors and the use of powerful platforms and computational algorithms, enable increased efficiency in decision making. It is not limited though to encoding the laws of war, so that the robot will decide when to apply lethal action.

6.8 Moral and ethical issues

The use of autonomous technologies is neither completely morally acceptable, nor is it completely morally unacceptable as Just war theory concludes [41]. However it is a serious issue to embed ethics in a war robot with a mission to apply lethal force.

7 Future perspective

In the not too distant future, “Intelligent Entities” (robots, smart devices, smart vehicles, smart buildings, etc) will share the everyday living environment of human beings spanning from their household to the work environment. Such machines will eventually be integrated in all missions offering support and assistance and are expected to communicate with soldiers and officers in a natural and intuitive way. Such entities are a growing industry from both research and commercial perspectives.

Future wars will surely involve Intelligent robots which will get into battle alone, or in co-operation with human combatants.

The facts indicate a trend that humans progressively stand off from the process of decision-making and responsibility on battle field operations. Despite the painstaking studies on the field, it is not easy to forecast when the direct control of lethal force and the responsibility of making moral decisions will completely be entrusted to intelligent robots, but it will eventually happen.

Advanced coding of ethics will be embedded in intelligent robots so that they develop moral behavior.

Experts' committees in collaboration with global associations may develop a universal framework of directives and legislation for the development of autonomous robots, necessary to regulate the development and proliferation of intelligent robotic systems in warfare.

8 Conclusions

There are various drivers that lead robotic systems' development. Evolution in robotics is performed in all respects. Robots are becoming Intelligent, more efficient, more diverse, more cost effective, better in all respects. All the advanced capabilities of intelligent robots enable their extended use in various tarks and missions within the defense sector. The already developed robots have been used with success, for a great variety of applications in the battlefield and elsewhere. Year by year, through many shapes and functionalities (hence the extended taxonomy), they will be ubiquitous in the war field.

The increased use and deployment of intelligent robots in warfare will induce quite a lot impacts. Their application in warfare will induce changes in the organization, composition, and structure of military forces in the long term.

As well there may be changes in the tactics of battle: versatile hybrid forces of robotic systems and humans, which can be rapidly deployed.

Changes in military personnel composition will be expected. That can be described as fewer people on the battle field, need for new skills and recruiting changes.

More robotics' specialists and technicians will be employed in the military forces. Human staff may train robots and robots may train human staff. The training process will definitely require less time and costs.

As robots become more efficient, more versatile and cost effective, they will facilitate increased accuracy for weapons, increased flexibility and faster deployment for military forces, fewer casualties in battle field, lower-cost for the systems, greater success for the missions.

The increased use and deployment of intelligent robots in warfare will also induce impacts in strategy and policies, in culture, society and economy at large.

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