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An analysis of the best available unmanned ground vehicle in the current market with respect to the requirements of the Turkish Ministry of National Defense

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NAVAL POSTGRADUATE SCHOOL

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MBA PROFESSIONAL REPORT

An Analysis of the Best Available Unmanned Ground Vehicle in the Current Market with Respect to the Requirements of the Turkish Ministry of National Defense

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December 2011

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13. ABSTRACT *(maximum 200 words)*

Today, Unmanned Ground Vehicles (UGVs) provide significant supporting capabilities in military operations worldwide. When UGVs are used to their full potential, the number of casualties is decreased and the combat effectiveness of warfighters is increased. UGVs are being developed in different sizes to meet different mission capability requirements. The employment of available UGVs and the development of new UGV capabilities have been rising steadily.

Countries have started giving more importance to UGVs, and they are now being employed all over the world. The Turkish Ministry of National Defense (MND) can use the advantages of UGVs in a number of ways to assist in its efforts against terrorist activities.

The purpose of this MBA project is to conduct an analysis of the best available UGV in the current market with respect to the requirements of the Turkish MND. After providing some background and market research on UGVs, we will explore their capabilities and their capability gaps in regard to the requirements of the Turkish MND. In the end, this project will determine the best available near-term UGV for the Turkish MND by employing the Analysis of Alternatives (AoA) method of the U.S. Defense Acquisition System.

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AN ANALYSIS OF THE BEST AVAILABLE UNMANNED GROUND VEHICLE IN THE CURRENT MARKET WITH RESPECT TO THE REQUIREMENTS OF THE TURKISH MINISTRY OF NATIONAL DEFENSE

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Submitted in partial fulfillment of the requirements for the degree of

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LIST OF ACRONYMS AND ABBREVIATIONS

AF	Air Force
ANS	Autonomous Navigation System
AoA	Analysis of Alternatives
ARCIC	Army Capabilities Integration Center
ARTS	All-Purpose Remote Transport System
ARV	Armed Reconnaissance Vehicle
ARV-A(L)	Armed Robotic Vehicle - Assault (Light)
ATR	Automated Target Recognition
CCD	Charge-Coupled Device
CBRN	Chemical, Biological, Radioactive, Nuclear
CCC	Computing Community Consortium
CML	Cooperative Mapping and Localization
COC	Combat Operation Center
COE-DAT	Centre of Excellence-Defense Against Terrorism
CONEMP	Concept of Employment
CONOPS	Concept of Operations
COP	Common Operational Picture
CoTs	Computing Technologies, Inc.
COTS	Commercial Off-the-Shelf
C4I	Command, Control, Communications, Computers, and Intelligence
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
DAU	Defense Acquisition University
DCS	Direct Commercial Sales
DoD	Department of Defense
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel and Facilities
DR20	Dragon Runner 20

E-IBCT	Early Infantry Brigade Combat Team
EOD	Explosive Ordnance Disposal
EUROP	European Robotics Technology Platform
FBI	Federal Bureau of Investigation
FCS	Future Combat System
FLIR	Forward-Looking InfraRed
FMF	Foreign Military Financing
FMS	Foreign Military Sales
FP	Force Protection
GPS	Global Positioning System
GRUNT	GRound UNiTs
HazMat	Hazardous Material
HFI	Hostile Fire Indicator
HRI	Human-Robot Interaction
HWAD	Hawthorne Army Depot
IDF	Israel Defense Force
IED	Improvised Explosive Device
IMET	International Military Education and Training
IMU	Inertial Measurement Unit
INCLE	International Narcotics Control and Law Enforcement
IR	Infrared
JRP	Joint Robotics Program
KPP	Key Performance Parameter
LIDAR	Light Detection and Ranging
LOA	Level of Autonomy
LOS	Line of Sight
LUGV	Large Unmanned Ground Vehicle
MAGIC	Multi Autonomous Ground-robotic International Challenge
MAGS	Mobile Autonomous Guard System
MARCbot	Multifunction, Agile, Remote-Controlled Robot

MAS	Multi-Agent System
MDARS	Mobile Detection Assessment Response System
MDS	Major Defense System
MEMS	Micro-Electrical Mechanical Systems
MND	Ministry of National Defense
MoD	Ministry of Defense
MoE	Measures of Effectiveness
MoP	Measures of Performance
MOUT	Military Operations in Urban Terrain
MT	Mission Task
MUGV	Medium Unmanned Ground Vehicle
MULE	Multifunctional Utility/Logistics & Equipment
NADR	Nonproliferation, Antiterrorism, Demining and Related Programs
NATO	North Atlantic Treaty Organization
N-LOS	Non-line-of-sight
NNSA	National Nuclear Security Administration
NNSS	Nevada National Security Site
NRC	National Research Council
OCU	Operator Control Unit
OE	Operational Environment
QC	Quantum Cascade
R&D	Research and Development
RF	Radio Frequency
RFID	Radio-Frequency Identification
ROC	Robot Open Control
RSTA	Reconnaissance, Surveillance, and Target Acquisition
SA	Situational Awareness
SLAM	Simultaneous Localization and Mapping
SME	Small and Medium Sized Enterprises
SSM	Under Secretariat for Defense Industries

SUGV	Small Unmanned Ground Vehicle
SWaP	Size, Weight, and Power
SWAT	Special Weapons and Tactics
SWORDS	Special Weapons Observation Remote Reconnaissance Direct Action System
TAF	Turkish Armed Forces
tEODor	Telerob Explosive Ordnance Disposal and Observation Robot
UAV	Unmanned Aerial Vehicle
UGCV	Unmanned Ground Combat Vehicle
UGS	Unattended Ground Sensor
UGV	Unmanned Ground Vehicle
UK	United Kingdom
UMS	Unmanned System
UN	United Nations
UPI	UGCV PerceptOR (Perception for Off-road Robotics) Integration
USV	Unmanned Surface Vessel
UUV	Unmanned Underwater Vehicle
UXO	Unexploded Ordnance
UVI	Under-Vehicle Inspection
VCI	Vehicle Cone Index
U.S.	United States

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Muzaffer Buyruk

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I. INTRODUCTION

A. BACKGROUND

According to Toksöz (2009), the state of international affairs during the Cold War period was defined as “bipolar stability.” Since then, former communist countries have repositioned themselves in international affairs, and a transition has taken place from a bipolar structure to a unipolar one. This change has been accompanied by much turmoil. Instability is the new character of world affairs. It has roots in ethnic conflicts, failed states, newly emerging states, separatist movements, regional tensions, economic rivalries, regionalism, globalization, emerging powers and, above all, terrorism. New types of threats – such as drug trafficking, human trafficking, migration, environmental problems, structural violence, questions of identity, separatism, religious fundamentalism, terrorism, energy security, water security, and economic recession – have replaced old ones, so that there are now more uncertainties than ever (Toksöz, 2009).

Among the new types of threats, terrorism has added a new dimension to the national security strategies and objectives of all countries. For example, the events of September 11, 2001, affected the national security strategies of the United States tremendously. This is manifest not only in its military operations in different regions of the world, but also in the daily lives of American citizens. New security policies in the airline industry are good examples of this. Mr. Y (2011) explores the change in the national security strategy of the U.S. by pointing out five major new changes/orientations within the global system:

- From control in a closed system[1] to credible influence in an open system[2]
- From containment[3] to sustainment
- From deterrence and defense to civilian engagement and competition
- From zero-sum to positive-sum global politics/economics
- From national security to national prosperity and security (Mr. Y, 2011)

The Republic of Turkey, as a North Atlantic Treaty Organization (NATO) member and an ally of the U.S., has also altered its national security strategies according to the new threats and transitions in the global system. Turkey is located in a problematic area of the world, surrounded by the Balkans, the Caucasus, and the Middle East. It has been affected by the spill-over effect of existing crises and instabilities within its neighborhood, so it categorizes any crisis or instability in the region as a threat to its own security. Instability in the region has provided a fertile ground for terrorism (Toksöz, 2009). Terrorists are especially concentrated in the southeastern part of Turkey where the Turkish Armed Forces (TAF) are fighting against terrorists determinedly and continuously. To support its success in the War on Terrorism, the Ministry of National Defense (MND) wants to acquire the latest technological Major Defense Systems (MDS) to strengthen the TAF and to modernize its current systems.

Today, many countries are making large investments to strengthen their military capabilities in order to attain their national security objectives. Each country wants to improve its defense strength by acquiring new systems. This acquisition is hampered by today's global economic crisis such that countries must create effective strategies and implement more efficiently than in the past. Turkey, as a developing country, procured its needed MDS up until the 1990s from other developed countries, especially from the United States. Using Direct Commercial Sales (DCS) or Foreign Military Sales (FMS) methods, the Turkish MND mostly signed procurement contracts for its MDS, including

[1] General Systems Theory by David S. Walonick, Ph.D., 1993, states: "A closed system is one where interactions occur only among the system components and not with the environment."

[2] General Systems Theory by David S. Walonick, Ph.D., 1993, states: "An open system is one that receives input from the environment and / or releases output to the environment."

[3] It is a United States policy using military, economic, and diplomatic strategies to stall the spread of communism, enhance the U.S.'s security and influence abroad. This policy is used during the Cold-War period by the U.S.

those for joint production programs, such as the F-16 program. However, since the mid-2000s, the Turkish defense industry has begun to produce systems uniquely designed to meet the needs of the Turkish Armed Forces (Savunma Sanayii Müsteşarlığı [SSM], 2011).

The level of investment in robotics systems for military and homeland security is increasing worldwide. According to the Economist article (2011), the U.S. has been investing in UAVs, and the usage of them in counter-terrorism operations has increased 1,200% since 2005. The UAVs' importance in the theater has been emphasized:

> Laden with sophisticated sensors and carrying Hellfire missiles and laser-guided bombs, they patrol the skies above Afghanistan, launch lethally accurate strikes against terrorists in the tribal areas of Pakistan, Yemen and Somalia and have helped NATO turn the tide against Muammer Qaddafi's forces in Libya. (The Economist, 2011)

The success of UAVs in the War on Terrorism has provided the impetus for governments to invest in other types of unmanned systems (UMSs), such as unmanned ground or maritime systems. The Turkish MND has been investing in such robotic systems and the Turkish defense industry has begun to produce its own uniquely designed platforms. The primary application of these robotic systems, based on the needs of the Turkish Armed Forces, has been UAVs. The Turkish Armed Forces plans to use UAVs against terrorists, just as the U.S. Armed Forces has used them in Afghanistan.

The Turkish MND keeps track of the current trends in defense industries all around the world and has observed the rising interest in unmanned ground vehicles (UGVs) and their many valuable attributes that can aid and complement warfighters on the battlefield. UGVs not only provide tactical commanders with increased mission capability, they also reduce risks to personnel, and they will most likely leverage the strength and capabilities of the Armed Forces in the War on Terrorism. Thus, this study will focus on this new trend. The first step in this analysis of UGVs is to determine the needed capabilities, capability gaps, and requirements of the Turkish MND. Then, this project will employ the Analysis of Alternatives (AoA) method of the U.S. Defense Acquisition System to determine the best available near-term UGV for the Turkish MND.

B. PURPOSE

The purpose of this MBA project is to conduct an analysis of the best available UGV in the current market with respect to the requirements of the Turkish MND. The current capabilities of the Turkish MND regarding UGVs will be explored by analyzing the Turkish MND's Technology Management Strategy. The requirements and capability gaps of the Turkish MND in regard to UGVs will be discussed within the analysis. This study will also provide a review of UMSs, with a specific focus on Unmanned Ground Systems: their types, supporting technology areas, and the current UGV market. Additionally, current UGV efforts in the Turkish Ministry of National Defense will be explored.

C. RESEARCH QUESTIONS

1. Primary Research Question

This research is primarily concerned with the question:

- What is the best available UGV in the current market with respect to the requirements of the Turkish MND?

2. Secondary Research Questions

This research is also concerned with these additional questions:

- What capabilities does the Turkish MND have with regards to UGVs?
- What are the capability gaps and requirements of the Turkish MND regarding UGVs?

D. SCOPE

This research focuses on UGVs and the best available UGV in the current market with respect to the requirements of the Turkish MND. Our decision to focus only on UGVs is justified as follows. First, UMSs are a broad subject to explore within a limited time frame. Second, there is growing attention to UGVs, even though the current trend for unmanned vehicles in the TAF is toward UAVs. Finally, in order to find the best available UGV, we needed to narrow our research area by focusing on the requirements of the Turkish MND for these vehicles (since the first and the most important step in acquiring a major defense system containing complexity, variability, and technological maturity is to define the needed capabilities, capability gaps, and requirements for that system). The depth of our analysis was driven by the availability of information and data from open literature resources.

E. METHODOLOGY

Our research starts with an overview of UGVs that explores UMS concepts, UGV types, supporting technology areas, and the current UGV market. After this overview, we explore current UGV efforts in the Turkish MND to determine the Turkish MND's current UGV capabilities. In this study, we employ the AoA model of the U.S. Defense Acquisition System. We apply this model to determine the capability gaps and requirements of the Turkish MND in terms of UGVs and to analyze the best available UGV in the current market with respect to the requirements of the Turkish MND.

F. ORGANIZATION OF STUDY

Chapter I is an introduction to our topic: "An Analysis of the Best Available Unmanned Ground Vehicle in the Current Market with respect to the Requirements of the Turkish Ministry of National Defense." It provides an overview of the purpose, research questions, scope, applied methodology, and organization of the project.

Chapter II provides an overview of UGVs. It begins with general UMS concepts and then explores UGVs by focusing on the types, supporting technology areas, and the current world market for UGVs. The goal of this overview is to provide readers with a background on UGVs and to conduct UGV market research.

Chapter III introduces the history of the Turkish defense industry and the Under Secretariat for Defense Industries. It then reviews the technology management strategy of the Turkish MND and current UGV efforts in the Turkish MND and the Turkish defense industry. The goal of this chapter is to understand the capabilities of the Turkish MND and defense industry regarding UGVs.

Chapter IV establishes an evaluation methodology to analyze the data collected from the open literature in Chapter V. The employed model is the AoA method of the U.S. Defense Acquisition System. First, we define the concept of operations, needed capabilities, capability gaps, threats, scenario, key performance parameters (KPPs), and mission tasks (MTs) / measures of effectiveness (MoEs) / measures of performance (MoPs). Then, we establish the methodology for our analyses – which are effectiveness analysis and risk analysis – and we explain the alternative comparison matrix. The goal of this chapter is to provide an overview of the AoA model employed in Chapter V.

In Chapter V, we employ the AoA framework to define the capability gaps and the requirements of the Turkish MND in terms of UGVs. Then, we perform an effectiveness analysis and a risk analysis, and we generate an alternative comparison matrix to decide the best available UGV with respect to the requirements of the Turkish MND.

The final chapter contains the conclusion of this study and describes how this study points to new perspectives and opportunities for further research.

II. OVERVIEW OF UGVS

This chapter will focus on unmanned ground vehicles (UGVs). We will first explore the concept of unmanned vehicles and provide information about UGVs. Then, we will explore supporting technology areas. Finally, we will examine the current UGV market and describe several examples of the UGVs from select countries.

A. THE CONCEPT OF UNMANNED SYSTEMS

At the end of the Cold War, most countries reduced the size of their military forces in spite of an increase in the number of conflicts and peacekeeping operations in the world. Therefore, countries have started to look for faster, cheaper, and more efficient systems to replace human beings and keep their personnel out of harm's way as much as possible. Technologically developed countries have started to use robotic systems in their military forces to perform many tasks, such as the suppression of enemy forces and mine detection and clearance (Wilson, 1997).

The greatest benefit of robotic systems is that they decrease danger to military personnel. They can increase the speed of military tempos without common human weaknesses like tiredness, fear, and stress. Therefore, the introduction of unmanned vehicles can create new and innovative operational concepts and reduce the chance of friendly fire (IHS Jane's, 1997).

UMSs have the ability to perform tasks that manned vehicles cannot, and they can provide force multiplication for the success of missions in a way that is affordable for a nation (U.S. Department of the Navy, 2007). They can perform routine, repetitive, or physically challenging tasks and provide necessary distance while operating on dirty or risky missions. They have saved the lives of many military personnel in different places and have great value in combat (U.S. Army Requirements Capabilities Integration Center [ARCIC], 2010).

The Department of Defense's (DoD) "Unmanned Systems Safety Guide for DoD Acquisition" (2007) defines UMSs as:

> An electro-mechanical system that is able to exert its power to perform designed missions and includes the following: (1) there is no human operator aboard, (2) manned systems that can be fully or partially operated in an autonomous mode, and (3) the system is designed to return or be recoverable. The system may be mobile or stationary, and includes the vehicle/device and the control station. Missiles, rockets and their submunitions, and artillery are not considered UMSs. UMSs include, but are not limited to: unmanned ground vehicles (UGVs), unmanned aerial/aircraft systems (UAVs), unmanned underwater vehicles (UUVs), unmanned surface vessels (USVs), unattended munitions, and unattended ground sensors (UGSs). (p. 1)

B. WHAT ARE UGVs?

Ivlev and Weiss (2011) define UGVs as:

> In the broadest "dictionary" sense, an unmanned ground vehicle is any piece of mechanized equipment that moves across the surface of the ground and serves as a means of carrying or transporting something, but explicitly does NOT carry a human being. In other words, it must be controlled remotely, or its actions must be pre-determined. A UGV must have some sort of on-board artificial intelligence, allowing it to make decisions, and must adapt to situations quicker than any human can imagine. (p. 1)

According to the DoD (2006), a variety of prototypes, both commercial off-the-shelf (COTS) purchases and fielded systems of UGVs, can serve in broad mission areas such as improvised explosive device (IED) detection and defeat, scouting, explosive ordnance disposal (EOD), force protection (FP), countermining, unexploded ordnance (UXO) clearance, among others. They come in a myriad of sizes, from a hand-launched Throwbot prototype that weighs less than a pound to large systems like the Abrams Panther mine-clearing vehicle that weighs over forty tons (DoD, 2006).

The DoD's "Unmanned Ground Vehicle Master Plan" (1991) lists the following potential payoffs of UGVs:

- Reduced risk to human life and increased operational flexibility in combat or other hazardous environments

- Economy of manpower or reduced costs in operations done repetitively (e.g., logistics) where manpower savings more than offset investments in equipment

- Reduced training costs and increased training realism

- Improved performance where automated systems either perform better than humans or eliminate the system compromises required by human physiological limits (creature comfort, fear, fatigue, vibration, etc.)

- Force multiplication where operators with UGVs bring substantially more capability to bear than would be possible by individual troops without UGVs (p. 2)

In summary, the National Research Council (NRC, 2002) has said UGVs can help and complement forces in military operations, decreasing casualties and increasing the combat effectiveness of soldiers.

The different categories of UGVs provide a wide range of mission capabilities with various degrees of autonomy regarding command and tasking functions, terrain reasoning, military maneuvering, and mobility design (NRC, 2002). An NRC report (2002) describes four generic classifications of UGV capabilities that are based upon relevance to potential missions, level of autonomy, and the challenge that must be implemented. Table 1 lists the UGV capability classes with potential mission function applications.

Capability Class	Other Possible Applications
Tele-operated ground vehicle	Mine detection, mine clearing, engineer construction, EOD/UXO, materials handling, soldier-portable reconnaissance/surveillance
Semiautonomous preceder/follower	Supply convoy, medical evacuation, smoke laying, indirect fire, reconnaissance/surveillance, physical security
Platform-centric autonomous ground vehicle	Remote sensor, counter-sniper, counter-reconnaissance/ infiltration, indirect fire, single outpost/scout, chemical/biological agent detection, battle fire, single outpost/scout, chemical/biological agent detection, battle damage assessment
Network-centric autonomous ground vehicle	Deep RSTA, combined arms (lethal direct fire/reconnaissance/ indirect fire for small unit defense or offense), static area defense, MOUT reconnaissance
RSTA = reconnaissance, surveillance, and target acquisition; MOUT = military operations in urban terrain.	

Table 1. UGV Capability Classes and Potential Mission Function Applications (From NRC, 2002)

Munk (2003) gives examples of different types of UGVs that perform different tasks in military operations. These examples include:

- Soldier UGVs carried by one or more soldiers to perform a variety of tasks (reconnaissance, surveillance, door breach, smoke generation, etc.) in support of dismounted soldiers.
- Transport (mule) UGVs that are towed to the operational area by a larger vehicle to perform transportation missions (dismounted troop material services or supplies movement). Armed reconnaissance vehicle UGVs that perform armed RSTA missions and are capable of man in-the-loop weapon fire via a C4ISR network.
- Unmanned ground combat vehicles (UGCVs) that include robotic direct fire and robotic non-line-of-sight fire weapon systems. (p. 200)

1. UGV Types

U.S. Army Developmental Test Command (2009) identifies three categories of UGVs based upon size, mode of operation, and weapon type.

a. Size

Micro UGV: An unmanned ground vehicle weighing less than 10 lbs.

SUGV (Small Unmanned Ground Vehicle): An unmanned ground vehicle weighing less than 200 lbs.

MUGV (Medium Unmanned Ground Vehicle): An unmanned ground vehicle weighing between 200 and 2,000 lbs.

LUGV (Large Unmanned Ground Vehicle): An unmanned ground vehicle weighing more than 2,000 lbs.

b. Mode of Operation

Tethered: A mode of control wherein the human operator controls the UGV through a direct, wired connection. An example of such connection would be a fiber-optic cable. Typically a line of sight (LOS) must be maintained under tethered operation; however, under certain circumstances, a LOS isn't necessary (i.e., operation in a tunnel, around corners).

Remote Controlled: A mode of control wherein the human operator must dedicate 100 percent of his/her attention to system operation without benefit of sensory feedback from the vehicle. A LOS must be maintained with the vehicle under remote control operation.

Tele-operated: A mode of control wherein the human operator has control of the UGV through cues provided by video, audio and digital feedback. The human operator controls the UGV through a wireless connection transmitted over radio frequencies (RF). The human operator must dedicate 100 percent of his/her time to operating the UGV. A LOS does not necessarily need to be maintained under teleoperation.

Autonomous: A mode of control wherein the UGV is self-sufficient. The human operator can program a mission for the UGV, but the UGV will execute the mission without any human interaction. There are varying levels of autonomy in regards to the level of human interaction with the UGV.

Semi-autonomous: A UGV that has multiple modes of control occurring simultaneously to include at least one autonomously controlled function. The level of semi-autonomy can vary greatly from UGV to UGV and will tend to be used extensively on weaponized UGVs (i.e., a weaponized UGV equipped with an Autonomous Navigation and Obstacle Avoidance System, but with tele-operated, operator-controlled weapon functions).

Manned: A mode of control wherein the UGV is directly controlled by a human operator through the use of a steering wheel.

c. Weapon Type

Weaponized, projectile: A UGV equipped with any device that launches a projectile (i.e., machine gun, smoke grenades, and lane markers).

Weaponized, non-projectile: A UGV equipped with any energetic device that can affect the area around the vehicle without launching a projectile (i.e., acoustic, laser, sonic devices).

Weaponized, non-lethal projectile: A UGV equipped with a weapon or device that launches a non-lethal projectile (i.e., rubber bullets, pepper balls, netting, paint balls).

Non-weaponized: A UGV not equipped with a weapon or device that affects the environment around the vehicle. (pp. 3–4)

D. SUPPORTING TECHNOLOGY AREAS

The DoD's "FY2009–2034 Unmanned Systems Integrated Roadmap" (2009) outlines the key capabilities of unmanned vehicles. Whereas UAVs need to fly in and around urban environments, and UUVs and USVs must be able to work in and around ports and marinas, UGVs must be able to operate within buildings, tunnels, and streets (where they have to deal with traffic, pedestrians, and even curbs, drains, and trash). Within buildings, they must be able to traverse stairs and elevators, open doors, and access desks, file drawers, and cupboards – places where there is no Global Positioning System (GPS) signal. UGVs must have the ability to navigate in changing terrain and under various payload, range, and endurance requirements. In addition, they must be able to perform complex manipulation of objects in order to imitate humans performing complex tasks. Therefore, there are many key capabilities unique to UGVs. Of key importance is the ability to behave autonomously (DoD, 2009).

Sellers, Ramsbotham, Bertrand, and Karvonides (2008) argue that state-of-the-art technology is not capable of a fully autonomous, on-board sensor, perception-based operation (navigation and control without the use of preprogrammed map information, a GPS, or other cooperative navigation aids). However, countries are looking for ways to improve these areas of technology. The United States, France, Germany, and Japan are currently giving great attention to these improvements, while Canada, Israel, and the United Kingdom (UK) have the capability to advance in these technology areas. Other countries that have the potential to contribute improvements are Australia, South Korea, Switzerland, Sweden, Italy, China, Russia, Singapore, and Finland (Sellers, Ramsbotham, Bertrand, & Karvonides, 2008).

Table 2 lists the key capabilities and consolidates the projected evolution of them for UGVs. Most importantly, the level of autonomy allows for a high level of human control/intervention today. However, it should progress to a level where there is high level of human oversight (DoD, 2009).

	2009 Evolutionary Adaptation	2015 Revolutionary Adaptation	2034
Maneuverability	Simple Task/Man Dependent SA/Off Board SA	Limited Adaptation, Real Time, and Planning Sense and Avoid	Fully Real-Time Planning, Team of Team Coll., Fully Auto/On Board SA
Speed	20 Mph	45 Mph	90 Mph
Survivability	Basic Teleoperations		Fully Auto with Real Time, Urban Combat, On-Off Road Operations, Hostile Environment
Environment	Basic Tasks / Tele-operated	Human Approves Decisions	Fully Auto, Approaching Zero Human Interaction
Commands	Physical Human Machine Interfaces	Scripted Voice Command/Hand Signals	Natural Language Understanding
Collaboration	Individual System	Teaming w/in Domain Collaboration Across Domains	Teamed Collaboration
Frequency	Constrained RF	Frequency Hopping	Multi-Frequency Communications
Mission Complexity	Operator Controlled		Autonomous Adaptive Control Behaviors
Environmental Capability	Limited Environmental Difficulty		All Weather Environmental Difficulty
Product Line	Mission Package Product Line Dependent		Product Line Independent
OPSEC	Signature High		Signature Low
Operational Control	1 Operator / Platform	1 Operator / Domain	1 Operator / Team
Bandwidth	Limited	Advanced Bandwidth Management	Autonomous Bandwidth
Mission Endurance	Hours	Days / Months	Years
Maintenance	Operator		Automated
Awareness	Sensor Data	Situational Awareness	Actionable Information

Table 2. Key Capabilities for UGVs (From DoD, 2009)

According to an NRC report (2002), every UGV should have a mobility platform, along with sensors, computers, software (including modules for perception, navigation, learning/adaptation, behaviors and skills, human–robot interaction, and health maintenance), communications, and power sources. It may also have a separate mission package that can be adjusted based on the role of the UGV in the mission. The same report describes supporting technology areas required by UGVs illustrated in Figure 1 (NRC, 2002).

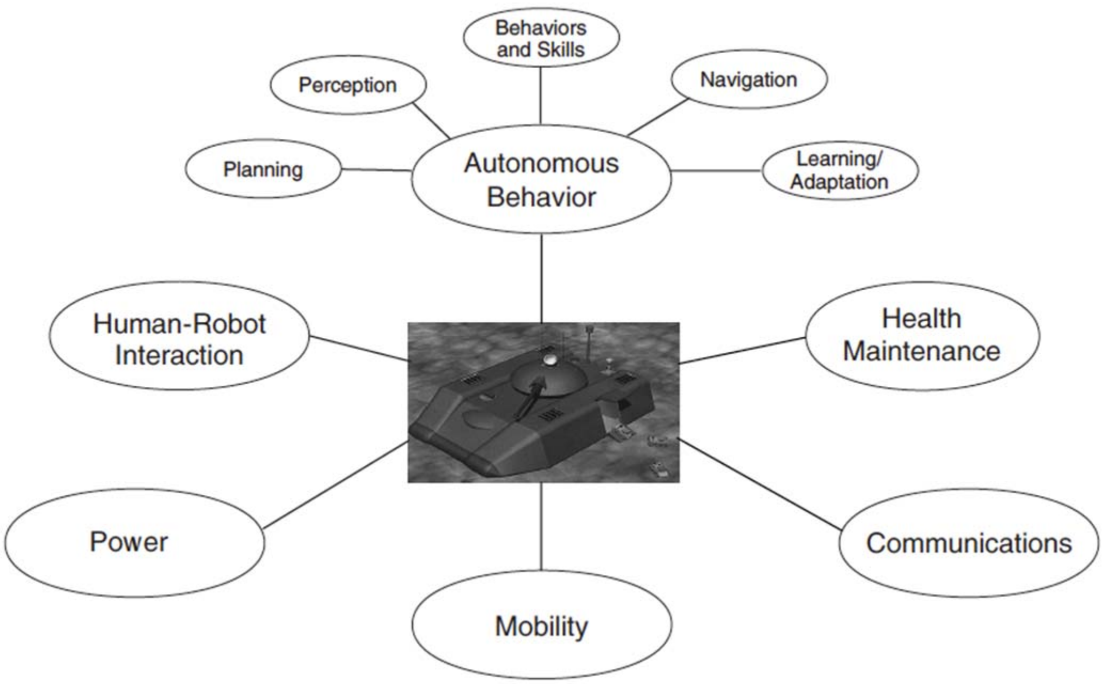

Figure 1. UGV Supporting Technology Areas (From NRC, 2002)

1. Autonomous Behavior

Ireland (2010) discusses the definition of autonomy:

> In general terms, autonomy is defined as "the quality or state of being self-governing". Within the realm of unmanned systems, however, a more specific definition is necessary. At the 2003 Performance Metrics for Intelligent Systems Workshop, Huang, Messina, and Albus defined unmanned systems autonomy as "its own capability to achieve its mission goals. They further stated that the more complex the mission goals are, the higher the level of autonomy required, and that levels of autonomy are proportional to the system's capability to perceive, plan, decide, and then act. (p. 8)

According to Jun (2007), autonomy relates to systems that have the ability to operate in an actual environment for a long time without external support. At the present time, fully autonomous systems have not yet been developed (Jun, 2007).

State-of-the-art military ground robots are remotely operated or tele-operated systems (even though prototypes with a certain degree of autonomy have been demonstrated). Autonomous systems are dependent upon preprogrammed motion or the ability to respond to simple sensor input. These systems do not have (or have only limited) capabilities to interpret on-board sensor data (Holste, Ciccimaro, & Dudenhoeffer, 2009).

In Ho's study (2006), "FY2005 Joint Robotics Program (JRP) Master Plan" lays out an evolution roadmap (as depicted in Figure 2), which shows that robot autonomy will be achieved on the battlefield by 2020.

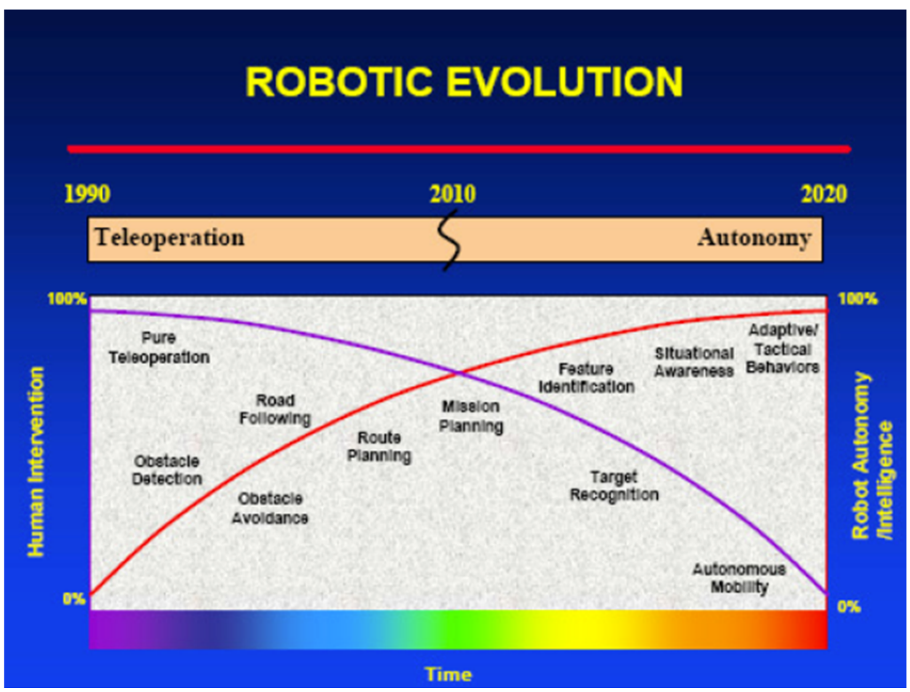

Figure 2. Robot Autonomy by 2020 (From Ho, 2006)

According to an NRC report (2005), defining the level of autonomy (LOA) is necessary to classify systems for comparison purposes. There is no consensus on a single LOA scale across the wide range of users.

The same report shows an LOA scale created by the U.S. Army for the Future Combat System (FCS) Program, as given in Table 3 (NRC, 2005).

Level	Level Description	Observation Perception and Situation Awareness	Decision-Making Ability	Capability	Example
1	Remote control	Driving sensors	None	Remote operator steering	Basic teleoperation
2	Remote control with vehicle state knowledge	Local pose	Reporting of basic health and state of vehicle	Remote operator steering commands, using vehicle state knowledge	Teleoperation with operator knowledge of vehicle pose situation awareness
3	External preplanned mission	World model database—basic perception	Autonomous Navigation System (ANS)-commanded steering based on externally planned path	Basic path following, with operator help	Close path following intelligent teleoperation
4	Knowledge of local and planned path environment	Perception sensor suite	Local plan/replan world model correlation with local perception	Robust leader-follower with operator help	Remote path following—convoying
5	Hazard avoidance or negotiation	Local perception correlated with world model database	Path planning based on hazard estimation	Basic open and rolling semiautonomous navigation, with significant operator intervention	Basic open and rolling terrain
6	Object detection, recognition, avoidance or negotiation	Local perception and world model database	Planning and negotiation of complex terrain and objects	Open, rolling terrain with obstacle negotiation, limited mobility speed, with some operator help	Robust, open, rolling terrain with obstacle negotiation
7	Fusion of local sensors and data	Local sensor fusion	Robust planning and negotiation of complex terrain, environmental conditions, hazards, and objects	Complex terrain with obstacle negotiation, limited mobility speed, and some operator help	Basic complex terrain

8	Cooperative operations	Data fusion of similar data among cooperative vehicles (such as UAVs)	Advanced decisions based on shared data from other similar vehicles	Robust, complex terrain with full mobility and speed. Autonomous coordinated group accomplishments of ANS goals with supervision	Robust, coordinated ANS operations in complex terrain
9	Collaborative operations	Fusion of ANS and reconnaissance, surveillance, and target acquisition (RSTA) information among operational force UGVs	Collaborative reasoning, planning, and execution	Accomplishment of mission objectives through collaborative planning and execution, with operator oversight	Autonomous mission accomplishment with differing individual goals and little supervision
10	Full autonomy	Data fusion from all participating battlefield assets	Total independence to plan and implement to meet defined objectives	Accomplishment of mission objectives through collaborative planning and execution, with operator oversight	Fully autonomous mission accomplishment with no supervision

Table 3. Levels of Autonomy in the U.S. Army Scale for the Future Combat System (From NRC, 2005)

The components of the entire system need computer processing power, which is a function of speed and memory and consists of related software and algorithms. There is a direct connection between computing power and advances in autonomous capability. The relationship between processor speed and memory is presented in Figure 3 (Ireland, 2010).

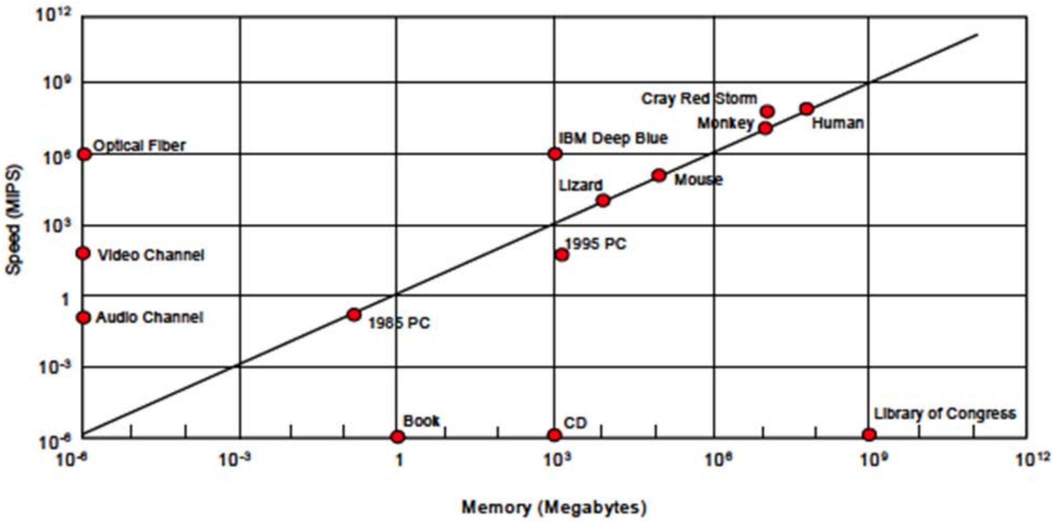

Figure 3. Relationship of Processor Speed and Memory (From Ireland, 2010)

Raymond Kurzweil argues in his book *The Singularity Is Near: When Humans Transcend Biology* that a computer will pass the Turing test by 2029 and will be able to "think" like a human. He also argues that several military UAVs and UGVs will be 100% computer-controlled by 2025 ("The Singularity Is Near," n. d.).

According to Arkin (2009), teams of autonomous systems and human soldiers will cooperate on the battlefield, as opposed to armies of unmanned systems functioning by themselves. The age of full autonomy for armed robots will come in the future once they are able to hunt, authenticate, and kill a target without any human intervention (Arkin, 2009).

a. Perception

European Robotics Technology Platform (EUROP, 2009) defines perception as "the robot's ability to build and interpret representations of the physical world from sensed data" (p. 33).

The perception system develops a world map, using data from sensors to build a representation of the world around the UGV. A set of software modules in the perception system transforms lower-level, image-processing functions to higher-level reasoning by using geometry, color, or other properties of the objects to classify the objects in the scene. To verify or refine the UGV's internal estimate of its location (recognize landmarks), a perception system must be able to detect, classify, and locate a number of natural and artificial features (NRC, 2002).

Specific perception system objectives include a road following, following a planned path cross-country, and obstacle avoidance. These are obtained from the required vehicle speed and characteristics of the assumed operating environment (e.g., obstacle density, visibility, illumination [day/night], weather [which affects visibility and illumination but may also change feature appearance]) (NRC, 2002).

The NRC report (2002) summarizes perception system tasks, as given in Table 4.

On-Road	**Off-Road**
Find and follow the road	Follow a planned path subject to tactical constraints.
Detect and avoid obstacles	Find mobility corridors that enable the planned path or that support re-planning.
Detect and track other vehicles	Detect and avoid obstacles.
Detect and identify landmarks	Identify features that provide cover, concealment, vantage points or as required by tactical behaviors. Detect and identify landmarks. Detect, identify, and track other vehicles in formation. Detect, identify, and track dismounted infantry in force.

Table 4. Perception System Tasks (From NRC, 2002)

UGVs have the challenge of operating in any weather (rain, fog, snow) and changing terrain caused by the weather. They must operate during day or night and contend with dust, wind, or other battlefield obscurants (DoD, 2009; NRC, 2002). They must be able to make decisions in situations, such as when the ground becomes slippery as a result of rain or when the roads are covered with snow (DoD, 2009).

EUROP (2009) makes predictions about the future development of perception technologies, as illustrated in Table 5.

Timeframe	Developments
Short-term (2010)	Sensor fusion is task-specific and relies on calibration; limited by processing power; use of attention mechanisms
Mid-term (2015)	Advanced task-dependent sensor fusion; multiple sensor modalities; step change in visual servoing; known events interpreted
Long-term (2020+)	Sensing on chip; perception techniques take over from fusion (closer to human perception system); no longer task-dependent

Table 5. Perception Technology Developments (From EUROP, 2009)

b. Navigation

EUROP (2009) explains that "Navigation is concerned with controlling movement. It relies on mapping, localization, and collision avoidance" (p. 31).

Navigation is a big problem for UGVs. An NRC report (2002) defines the elements related to navigation:

- Current location (both absolute and relative);
- Directions to desired location(s), such as final destination or intermediate waypoints;
- Aid in situational awareness (SA), including providing the location of friendly forces and targets over a large region;
- Map of immediate surroundings, how to navigate about the immediate surroundings and how to navigate to the next waypoint or final destination;
- The detection of nearby hazards to mobility. (p. 51)

The navigation module uses algorithms, such as Simultaneous Localization and Mapping (SLAM), to learn a "map" of its environment and uses that map as a basis for planning navigation. Studies of SLAM, also called Cooperative Mapping and Localization (CML), influenced the development of robots deployed in real applications (Bekey, et al., 2008).

The UGV's current position and poses (roll, pitch, and yaw) in absolute coordinates are monitored by the navigation system that supports the conversion of sensor data into an absolute frame of reference. For this operation, the system uses a number of independent means, such as an Inertial Measurement Unit (IMU), GPS, and odometry – with estimates from these sources combined by a Kalman filter, or something of the kind (NRC, 2002).

Navigation has connection with certain key technology areas, such as perception, path planning, behaviors, human–machine interface, and communications. One of the primary goals of the navigation system is to help give enough information to enable near- autonomous mobility for the UGV (NRC, 2002).

EUROP (2009) indicates the future developments of the navigation technologies, as given in Table 6.

Timeframe	Developments
Short-term (2010)	Navigation expensive (computation & sensors); localization and mapping in controlled environments solved
Mid-term (2015)	Some perception based localization; SLAM for challenging environments; collision avoidance considers dynamic objects
Long-term (2020+)	SLAM in unconstrained environments; collision avoidance with dynamic, non-cooperative obstacles through perception

Table 6. Navigation Technology Developments (From EUROP, 2009)

Sensors are necessary for the navigation of the UGV, which must be able to sense its environment, use the relative locations of events and landmarks, and answer questions such as: Where am I? Do I have a map of this area? How do I move in order to accomplish my task? There are new sensor technologies, like Light Detection and Ranging (LIDAR), which allow robots to detect obstacles and landmarks, and then combine input about them with its navigation strategies to generate depth maps of solid objects (Bekey, et al., 2008).

To date, sensor developments are not focused on the needs of ground robots. Sensors developed for military applications are mostly for long-range target detection and are large (e.g., 8 in. optics), heavy, and have a very narrow field of view. Video and infrared (IR) imagers, stereo video systems, scanning laser rangefinders, millimeter radars, and ultrasound sensors are typical examples of mobile robot sensors (NRC, 2005).

EUROP (2009) shows the future developments of the sensor technologies, as illustrated in Table 7.

Timeframe	Developments
Short-term (2010)	Gradual replacement of special hardware (frame grabbers, cameras…); 3D vision sensors in low resolution
Mid-term (2015)	Higher frame rate of visual sensors; greatly improved 3D vision sensors; no moving parts in laser scanners
Long-term (2020+)	Visual processes on sensor or dedicated processors; multimodal sensing for intrinsic safety

Table 7. Sensor Technology Developments (From EUROP, 2009)

c. Planning

EUROP (2009) describes planning as "the computation and selection of paths, motions, actions, tasks, policies, procedures, and missions for goal-directed robot behavior" (p. 31).

Planning is a serious challenge in robotics. The current level of planning and control algorithms only enables the robots to perform in narrowly prescribed scenarios, using very complicated programming which is written by humans with great effort. Even perfect sensing and hardware might not allow robots to reach human performance in most situations (Computing Community Consortium [CCC], 2009).

Planning includes software for both path planning, which has a relationship with perception and navigation, and mission planning for UGVs (NRC, 2002).

The NRC report (2002) describes path planning as "the process of generating a motion trajectory from a specified starting position to a goal position while avoiding obstacles in the environment" (p. 55).

The NRC report (2002) also describes motion planning as:

> From a military perspective, autonomous mission planning goes well beyond path planning. It is the ability of the autonomous UGV to determine its best course of military action, considering synergistically the mission being supported by the UGV; enemy situation and capabilities; terrain, features, obstacles, and weather conditions; the UGV's own and

> friendly force situation and vulnerabilities; noncombatant information; time available; knowledge of military operations and procedures; and unique needs of the integrated mission package. (p. 57)

EUROP (2009) identifies future developments of the planning technologies, as given in Table 8.

Timeframe	Developments
Short-term (2010)	Manual programming superior to automated planning (optimized process path based on human experience); randomized motions as planning alternative
Mid-term (2015)	Automated mission and process planning using, for example, databases of expert knowledge
Long-term (2020+)	Autonomous, online planning for tasks of high dimensionality; learn from human (often interactively)

Table 8. Planning Technology Developments (From EUROP, 2009)

d. Behaviors and Skills

According to the NRC report (2002):

> A behavior is coupling of sensing and acting into a prototype, observable pattern of action. It can be innate, learned, or strictly a stimulus response (e.g., ducking when something is thrown at you). A skill is a collection of behaviors needed to follow a plan or accomplish a complex task (e.g., riding a bicycle). (p. 58)

Reflexive obstacle avoidance, road following, formation keeping, and steering to avoid tipping over on steep-sided slopes are common robot behaviors. How to develop these individual behaviors while integrating the multiple types of behaviors into a consistent system is still not entirely understood. However, this needs to be achieved (NRC, 2005).

UGV can move and perform work with the aid of software for Behavior and Skills. Taking the input from Perception, Navigation, and Planning, this software then integrates and transforms it into motor commands for the UGV. This software also enables the UGV to perform mission-specific functions that are dependent upon tactics, techniques, and procedures used in military operations (NRC, 2002).

Tactical behaviors related to military skills are necessary for the UGV to operate on the battlefield. Cooperative behaviors are another area that will allow UGVs to perform tasks with other unmanned systems, such as UAVs (NRC, 2002).

e. Learning/Adaptation

"Learning refers to adaptation of robot behavior through practice, experience or teaching" (EUROP, 2009, p. 32). The Learning/Adaptation technology area includes neural networks, fuzzy logic, and genetic algorithms, which are related to artificial intelligence. It also includes adaptive controls, which are related to control theory (NRC, 2002).

Learning/Adaptation software utilizes experience to improve system performance of a system, so the system improves over time and a more robust system can be achieved (i.e., the system can handle variability not initially anticipated by the system's programmers) (NRC, 2002).

EUROP (2009) indicates the future developments of the learning technologies, as illustrated in Table 9.

Timeframe	Developments
Short-term (2010)	Parts of robot systems use learning methods; well-defined conditions; learning from expert teacher
Mid-term (2015)	Essential parts of controllers use learning methods; learning by experience; learning by demonstration
Long-term (2020+)	Complete robotic systems use learning methods (learning by observation, flexible conditions)

Table 9. Learning Technology Developments (From EUROP, 2009)

2. Human-Robot Interaction (HRI)

> HRI covers the macrocosm of how intelligent agents work together in a system. It encompasses human–robot interfaces, which are specialized human–computer interfaces for the particular needs of HRI in a defined system but is much broader. HRI is not synonymous with human-centered computing, whereby computers augment human ability, but it is assumed that the principles of human-centered computing or design will be applied to HRI systems when appropriate. (NRC, 2002, p. 72)

The HRI area has been drawing the attention of a growing number of networking initiatives and dedicated events worldwide (Dillmann & Asfour, 2009). It explores how humans and robots can communicate with each other via interfaces, using a number of channels (EUROP, 2009). Multimodal interface technologies are the key aspect for HRI. They enable robots to "observe" humans and their environments by recruiting signals from multiple audio-visual sensors. Natural multimodal interaction is the basic issue in the HRI area and is dependent upon visual person localization and tracking and upon gesture and posture recognition, speech recognition, and dialogue processing (Dillmann & Asfour, 2009).

HRI covers the interaction of humans with multiple robots (particularly in times of stress and cognitive fatigue), the dynamic sharing of responsibilities between humans and robots (an accomplishment dependent upon the context), and reducing the impact of uncertainty and information overload. HRI is useful for decreasing training times and providing a common interaction mode for controlling UGVs and UAVs (NRC, 2002).

EUROP (2009) points out the future development of HRI technologies, as illustrated in Table 10.

Timeframe	Developments
Short-term (2010)	Mostly graphical or text-based interfaces; few haptic devices and use of human interaction channels; touch interfaces
Mid-term (2015)	Human interaction channels, which human has to learn; some tele-presence; haptic input devices; learning interfaces
Long-term (2020+)	Interaction using human channels utilizing cognitive approaches; neural interfaces; non-invasive brain interfaces

Table 10. HRI Technology Developments (From EUROP, 2009)

3. Mobility

The NRC report (2002) describes mobility as:

> The ability of the robotic vehicle to traverse a rough terrain without any perception. The mobility of a UGV is often expressed in terms of the size of an obstacle (both negative and positive) it can negotiate and still continue along a specified path. As pointed out in U.S. Army (1998), for several reasons a UGV must have a high degree of mobility:

- A high degree of mobility minimizes the perception burden.

- Timely mission accomplishment cannot be achieved if the platform has to spend its time searching for an easy path through difficult terrain.

- The best route for covert missions will mostly likely not coincide with the easiest mobility route.

- A high degree of mobility will keep the vehicle from becoming stuck, thus requiring human assistance. (p. 76)

UGVs can be grouped as wheeled, tracked, or hybrid (a combination of wheeled and tracked). Wheeled UGVs are simpler, quieter, and more reliable. Tracked UGVs are noisier, and the tracks can be broken easily, but they have better traction and floatation ability than wheeled vehicles on slippery surfaces (NRC, 2002).

A number of criteria are used to evaluate the mobility of a UGV. The criteria for discrete obstacle negotiation are the ability to achieve tree and stump knock-over, gap crossing, fording water, vertical step crossing, and tree and stump avoidance. The criteria for all-terrain mobility are horsepower per ton, axial twist, ground pressure, vehicle cone index (VCI), forward/reverse slope, side slope operation, side slope stability margin, width for rollover resistance, side-step clearance height, high-low speed range, and ground clearance (NRC, 2002).

UGV mobility technologies need to be improved for off-road terrain with the following additions: smart active-suspension systems, new tire materials with controlled inflation, and high-performance traction with slip control for each wheel. UGVs do not have the limitations of a human crew, but their mobility platforms must be integrated with perception technologies to avoid obstacles to compensate for replacing human crew with mechanisms (NRC, 2002).

The U.S. Army Logistics Innovation Agency report (2006) identifies the future developments of the mobility technologies. They are listed in Table 11.

Timeframe	Developments
Short-term (<2011)	Human assistance technology, such as the exoskeleton, will be available to carry heavy loads. Specialized robot platforms are being developed that will incorporate more than one mobility technology, such as tracks and wheels. Snake type robots will be used for traveling into openings and areas that are too small for normal robots or soldiers.
Mid-term (<2016)	Balancing, traction, and selective braking technologies as part of an active suspension will allow robotic systems to negotiate or climb over obstacles. Artificial muscles will be refined and come into common use. Legged systems will become ubiquitous with efficiencies that rival or exceed those of wheeled vehicles.
Long-term (<2026)	Electrostatic repulsion vehicles may be available for robotic systems. Robotic systems may have the ability to morph-into different types of mobility technology depending on the terrain and surroundings encountered.

Table 11. Mobility Technology Developments (From U.S. Army Logistics Innovation Agency, 2006)

4. Communication

According to EUROP (2009), the role of communication is "concerned with hardware and software communication within the system's time constraints in the context of its architecture" (p. 29).

Various high-priority applications require communication and networking technologies, both of which are essential for the remote distribution of robotic systems, accessing remote data or computing resources, and interacting with humans (CCC, 2009). Tethered (Ethernet, fiber optic, etc.) and wireless/RF are current technologies in the communication field (U.S. Army Logistics Innovation Agency, 2006).

Present military data links provide the ability to convey a particular set of information from one platform to another for UGV communications. It is a logistically complicated task to preplan and organize these communication channels. Planning these communication channels manually before the mission or controlling communication manually during the mission are two crucial steps that need to be accomplished (NRC, 2002).

Communication for mobility management is getting more important for network-centric operations. There should be network participants on station to provide relay when it is necessary. Communication differences between manned and unmanned systems require common vision and technical architecture, as well as compliance with common interface standards (NRC, 2002).

The communication bandwidth enables coordination between vehicles and has an essential role in planning the paths of multiple UGVs. If there is less bandwidth, there will be less coordination between systems (NRC, 2002).

Improved frequency bandwidth enables multiple UGVs (and other unmanned systems) to operate as a group – simultaneously and closely with one another. Since the frequency spectrum is limited physically, there are limited available frequencies for UGVs. In the future, available frequencies for multiple unmanned systems will be a problem because they will all need to operate simultaneously in a network (Moreau, 2005).

EUROP (2009) and a U.S. Army Logistics Innovation Agency report (2006) indicate the future developments of the communication technologies that are given in Table 12.

Timeframe	Developments
Short-term (2010)	Numerous specialized protocols; Ethernet-based communication starts to take over as de-facto standard.
Mid-term (2015)	New protocols using ontologies, logic, probabilistic or geometric models, rule sets, etc. Infrared quantum cascade (QC) lasers will become robust enough for wide use. Optical technology and managed frequency distribution will also emerge along with motes or Smart Dust for distributed sensing and ad hoc networking. Antenna technology will be improved by developments in Micro-Electrical Mechanical Systems (MEMS).
Long-term (2020+)	Components can figure out each other's protocols; components negotiate required quality of service. Advances may be seen in wireless communications through earth/objects or over the surface (direct beam, non-satellite applications)

Table 12. Communication Technology Developments (From EUROP, 2009; U.S. Army Logistics Innovation Agency, 2006)

5. Power / Energy

Energy storage and power delivery play a critical role in mobile and autonomous robots, specifying available payload, mission duration, and service interval (CCC, 2009).

Energy sources and their utilization rate are vital to robotic vehicles and today have various options that are dependent upon application. Small units can use a battery that is either rechargeable or non-rechargeable. Larger units can use motor-generator or hybrid-electric systems whose energy train needs to be fueled. The power train of robotic vehicles must fulfill the energy demands of mobility, housekeeping, and mission package (NRC, 2002).

There are two distinct but integrated parts of UGVs: the mobility package and the mission package. The mobility package is the basic platform providing navigation, sensing, and so forth. The mission package provides the capability to function in a mission, with items such as weapons, logistics carriers, or reconnaissance/scout hardware and software. The energy requirements for mission package will differ and range from a few watts for long periods of time to kilowatts for short periods of time (NRC, 2002).

Power delivery is crucial for fuel-based systems such as engines and fuel cells. Fuel cells could advance in power density, whereas they might not beat engines, which are optimized to a great extent and have clear efficiency trade-offs (CCC, 2009).

The NRC report (2002) discusses the issues with energy as follows:

> The most obvious factors impacting the energy supply are mission environment, mission time, vehicle mass, signature, cost, logistics support, size, and efficiency. These factors are not independent and they may be more severe and mission limiting for small robotic vehicles with the energy supplies that make up most of the mass and volume of the system. (p. 83)
>
> For high-energy missions, the following issues must be addressed: catalysts for reforming fuel, thermal rejection processes, stealth, and energy storage and replenishment. (p. 9)

NRC reports (1997, 2004) provide an overview of all power source alternatives and their potential for UGVs, as illustrated in Table 13.

Power System	State of the Art, 2003	Item Considered	Scaling Laws	Hostile Signature	Suppression Potential	Fuel	Autonomy Time
Primary battery (includes metal/air)	Mature.	Energy density. Safety. Power density. Environmental impact.	Known	Minimal	Excellent	None	Hours/ days
Secondary battery	Mature in commercial applications.	Energy density. Cycle life. Power density Safety and cost.	Known	Minimal	Excellent	None	Hours
Fuel cell (hydrogen)	Beta prototypes with various hydrogen sources tested in field.	Fuel reformers. Water management. Safety.	Known	Thermal	Excellent	Hydrogen	Days/ weeks
Fuel cell (methanol)	Beta prototypes developed at power levels of 20 to 50 W.	Fuel and fuel crossover. Catalyst. Cost.	Known	Thermal	Excellent	Methanol	Days/ weeks
Fuel cell (solid oxide)	Emphasis on small sizes. Laboratory prototypes in 20-W range. Research in high-capacity designs.	High temperature. Materials. Integration and systems.	Known				
Internal combustion	Commercial applications with motor-alternator combinations in 30 to 100 W/kg range. Efficiencies greater than 20% in 500-W sizes.	Fuels. Vibrations. Life.	Known	Thermal Acoustic	Moderate	Multifuel (Some special)	Days/ weeks
External combustion	100 W/kg specific power demonstrated for motor-alternator with efficiency of 29%. Laboratory 35- to 50-W systems available for beta prototypes; 1- to 2-kW beta prototypes available with ~20% system efficiencies. System efficiencies projected to be >20%.	Fuels. Specific power. System-specific energy. Signatures.	Known	Thermal	Moderate	Multifuel	Days/ weeks
Nuclear isotope	Not considered.	Safety. Environmental impact. Cost. Public acceptance.	Known	Thermal Nuclear	Moderate	Special	Month/ years

Table 13. Overview of All Power Source Alternatives (From NRC, 1997, 2004)

The U.S. Army Logistics Innovation Agency report (2006) describes possible future developments in power technologies. These are shown in Table 14.

Timeframe	Developments
Short-term	Fossil fuels and batteries will continue to be the primary power source. Incremental improvements to battery technology with 3:1 energy density advancements are expected using Zinc-air primary cells.
Mid-term (<2016)	12:1 energy density improvements are expected using Lithium-oxygen primary cell batteries. However, major power breakthroughs that could affect large-scale materiel movement are not likely to occur within the next 20 years.
Long-term (<2026)	Bio-scavenging, the conversion of plant or animal material into energy using fuel cells fed by bacterial metabolism will be an application to power robotic systems in the right settings. Power beaming could also become a viable technology, whether it is from satellites, lasers or other Radio Frequency (RF) technologies in the air or on the ground.

Table 14. Power Technology Developments (From U.S. Army Logistics Innovation Agency, 2006)

6. Health Maintenance

The NRC report (2002) says that...

> Health maintenance has two distinct flavors. One is making the robot more physically robust; the other is detecting, diagnosing, and recovering from component failures (or from degradations in performance that may lead to mission failures).
>
> Such failures as engine overheating, loss of communications, or flat tires have solutions that are not unique to unmanned systems. UGV health maintenance technologies resolve aspects of failures that are either unique to UGVs or require machine awareness. This specifically includes technologies targeted at preventing or mitigating failures of sensors or electronics for robot vehicles. (p. 88)

Vehicle health monitoring and maintenance ensures that robots function reliably and within acceptable parameters. Monitoring and maintenance also forecast its set of tasks for the future (e.g., a robot just a few hours away from needing an overhaul should not be tasked for a new mission). Mission failure might be inevitable in the event of subtle sensor failures leading to false positives or false negatives on targets, especially when operators do not suspect any fault (NRC, 2002).

Monitoring systems for UGVs should also assist maintenance technicians and increase the availability of the vehicle. Fault tolerance has characteristics similar to health monitoring and maintenance (NRC, 2002).

E. UGV MARKET

Countries have started to invest in UGVs and increase utilization of them. Figure 4 shows the distribution of UGVs throughout the world by country (Holste et al., 2009).

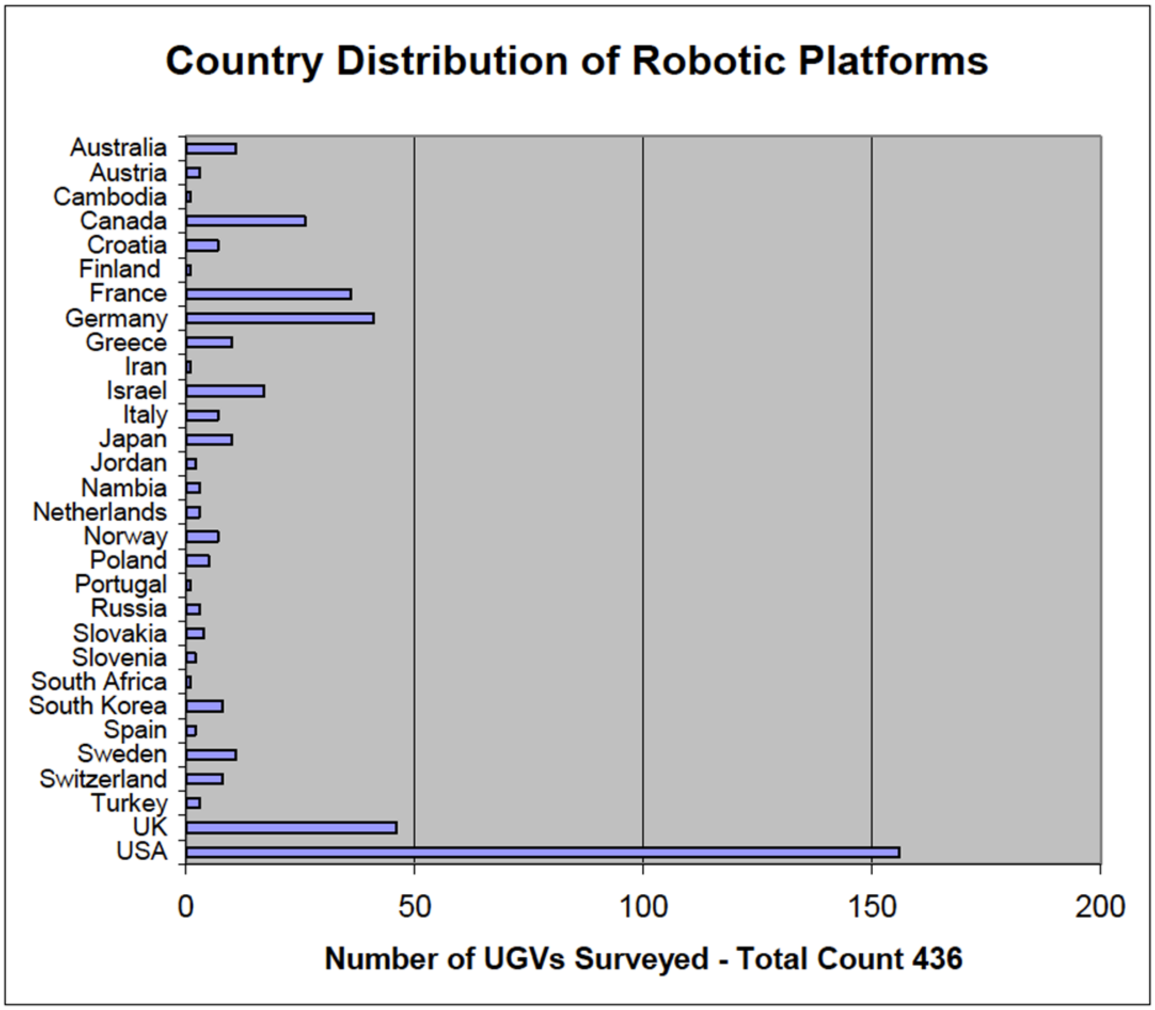

Figure 4. International Distribution of UGVs Reviewed in Market Study (From Holste et al., 2009)

According to Sellers et al. (2008), the countries with the most active military robotic programs are the United States, Canada, France, Germany, and Israel. Australia, Belgium, China, Croatia, Finland, Italy, Norway, Poland, South Korea, Singapore, Sweden, Switzerland and the United Kingdom have also made various degrees of effort.

Sellers et al. (2008) also argue that Japan is the technological leader in UGVs though it has not been working on miltary systems since investments in that area are unlucrative. The United States is the main country pursuing cutting-edge technology in military systems (Sellers et al., 2008).

1. United States

a. All-Purpose Remote Transport System (ARTS)

Figure 5. ARTS Fitted with Forklift Attachment (From IHS Jane's, 2010)

According to IHS Jane's (2010), the ARTS, developed by Wesco Manufacturing, is a large-tracked mine-clearing and EOD UGV used in service with U.S. forces. The ARTS, with its low-cost and survivability, can perform remote operations in several mission profiles (DoD, 2009). A set of tools and attachments (such as backhoe, bucket, and brush cutter) can be used to detect, assess, and render safe large IEDs, tackle large-vehicle bombs, and clear UXO from prepared areas (DoD, 2009; IHS Jane's, 2010). Both the front and rear of the ARTS can employ the loader arms. With its four-cylinder diesel engine, it can reach a speed of 11.2 km/h when it clears areas and clear 48 m^2/h of light vegetation (IHS Jane's, 2010). It has advanced navigation, control, and sensing systems and can be transported by helicopter or fixed-wing aircraft. Other specifications are given in Table 15 (DoD, 2009; IHS Jane's, 2010).

Height:	1.98 m (without antenna)		**Payload Capacity:**	3500 lbs.
Width:	1.67 m (without attachment)		**Endurance:**	4 to 7 h
Length:	2.89 m (without attachment)		**Remote Control Range:**	1.9 km
Weight:	2,948 kg (basic vehicle)			

Table 15. ARTS Characteristics (From DoD, 2009; IHS Jane's, 2010)

b. Crusher

Figure 6. Crusher (From IHS Jane's, 2011)

The Crusher is a large-wheeled combat UGV whose development is ongoing at Carnegie Mellon University (IHS Jane's, 2011). First introduced in 2006, it is an improved version of the Spinner UGV, was used in the UGCV PerceptOR (Perception for Off-road Robotics) Integration (UPI) program, and was developed to demonstrate technologies for the Future Combat System (FCS) program's Armed Reconnaissance Vehicle (ARV). Crusher was tested for mobility and autonomy between 2006 and 2008 at various sites around the U.S. (consisting of military bases/posts) where it traversed over 1400 km (DoD, 2009; IHS Jane's, 2011).

Its payloads include a stabilized, remote-operated small-arms mount with Forward-Looking InfraRed (FLIR), a mast-mounted, stabilized remote surveillance and target acquisition sensor with FLIR, and day cameras. It has a suspended and shockmounted steel skid plate which helps the vehicle to survive encounters with boulders and tree stumps. Forward of the vehicle are aids to help it survive collisions with similar other obstacles. Ground clearance is variable and the vehicle can rise up to 60 cm. It is a quiet vehicle since it has a hybrid electric drive system, where a 60 kW diesel engine charges a lithium ion battery. It boasts teleoperation and, according to the developer, full autonomy. It can also follow waypoints. Other characteristics are presented in Table 16 (IHS Jane's, 2011).

Height:	1.52 m		**Max side slope:**	>30°
Width:	2.59 m		**Curb clearance:**	>1.2 m
Length:	5.1 m		**Gap clearance:**	2.03 m
Weight:	5,987 kg (unloaded)		**Turning circle:**	Zero
Max speed:	42 km/h		**Max payload:**	3,628 kg
Max gradient climb:	>40°		**Payload volume:**	10.5 m^3 (main bay), 4 m^3 (front bay)

Table 16. Crusher Characteristics (From IHS Jane’s, 2011)

c. Gladiator

Figure 7. Gladiator (From IHS Jane’s, 2011)

A large wheeled multipurpose UGV, The Gladiator is under ongoing development at Carnegie Mellon University. It will perform combat, logistics, demining and reconnaissance missions (IHS Jane's, 2011).

Its desired system capabilities consist of:

- Reconnaissance, surveillance and target acquisition using day and forward-looking infrared cameras, laser rangefinder, acoustic sensor and GPS
- Obstacle breaching
- Direct fire using M240G 7.62 mm machine gun and M249 5.56 mm squad automatic weapon
- Obscuration
- Nuclear, biological and chemical agent reconnaissance and mapping
- Transport for crew’s weapons, ammunition, supplies or wounded personnel (IHS Jane's, 2011)

The desired system capabilities are further extended as follows:

Other key desired system capabilities include 4.5-9 kg for the man-wearable Operator Control Unit (OCU), conversion from transportation to operational mode in less than 10 minutes, a unit price of USD150,000 (2004), and that it be transportable by a MV-22 Osprey tilt-rotor aircraft, high-mobility multipurpose wheeled vehicle, or a CH-46/CH-53 helicopter. (IHS Jane's, 2011)

Other characteristics are listed in Table 17.

Height:	1.52 m	**Endurance:**	24 h; 8 h travelling and 16 h stationary surveillance (desired)
Width:	1.29 m	**Curb clearance:**	40 cm (desired)
Length:	2.03 m	**Max payload:**	181 kg
Weight:	1,270 kg	**Line of Sight:**	1.8 km
Max speed:	33 km/h (desired)		

Table 17. Gladiator Characteristics (From IHS Jane’s, 2011)

d. *Mobile Detection Assessment Response System (MDARS)*

Figure 8. MDARS (From IHS Jane's, 2011)

According to IHS Jane's (2011), the MDARS, developed by General Dynamics Robotic Systems, is a large wheeled patrol UGV in service with the U.S. Department of Energy and the U.S. Army. It has completed 8,000 hours of operation and more than 45,600 km of security patrols since October 2004 at Hawthorne Army Depot (HWAD) in Nevada where it performed missions like intruder detection, lock assessment, and inventory control (IHS Jane's, 2011).

The vehicle provides security and patrols DoD warehouses, airfields, ammunition supply depots, and port facilities. It can autonomously detect intruders to a range of 200 m and determine the status of inventory, barriers, and locks. For example, it can read 60,000 RFID tags affixed to sensitive/high-value stock and check 2,500 locks in a single-patrol shift. It can monitor radio-frequency (RF) tagged inventory and also determine if inventory has been moved and/or is missing from outdoor storage bunkers (IHS Jane's, 2011).

MDARS has other features, such as:

- Remote operation by joystick or autonomous, random patrol missions
- Up to 16 MDARS vehicles can be controlled simultaneously by a single operator with a single station

- Equipped with real-time obstacle-avoidance systems and 360° sensors

- Communications network of relay/repeaters installed on the ground provides redundant RF coverage of the entire patrol area (IHS Jane's, 2011)

Other characteristics of the vehicle are presented in Table 18.

Height:	2.62 m		**Endurance:**	16 h without refueling
Width:	1.64 m		**Max gradient climb:**	30°
Length:	2.92 m		**Curb clearance:**	27.94 cm
Weight:	1,360 kg		**Turning circle:**	6.4 m
Max speed:	32.1 km/h		**Line of sight control:**	4,000 m

Table 18. MDARS Characteristics (From IHS Jane’s, 2011)

e. Multifunctional Utility/Logistics & Equipment Armed Robotic Vehicle - Assault (Light) (MULE ARV-A(L))

Figure 9. MULE ARV-A(L) (From IHS Jane’s, 2011)

The MULE ARV-A(L) is a large wheeled multipurpose UGV. Its development is still ongoing at Lockheed Martin Missiles and Fire Control Systems. The Multifunctional Utility/Logistics & Equipment (MULE) vehicle was a part of the FCS Program which had three variants, including a transport version (MULE-T), an Armed Robotic Vehicle - Assault (Light) (MULE ARV-A(L)), and a counter-mine version (MULE-C). The FCS program was canceled in 2009, so the only continuing development of the MULE ARV-A(L) is under the U.S. Army's Early Infantry Brigade Combat Team (E-IBCT) program (IHS Jane's, 2011).

The MULE ARV-A(L) is 6x6 with hub motors on each wheel. Articulated axles, attached separately to each wheel, can adjust wheel position in all three dimensions and enable the vehicle to maneuver over irregular surfaces like low walls. The vehicle can operate on as few as three wheels should one of the wheels or axles be disabled (IHS Jane's, 2011).

The autonomous navigation capability of the vehicle was tested in a range of obstacle-crossing demonstrations in 2007 during which the vehicle showed it could overcome a 75-cm step and a 175-cm gap and could be expected to have a fording capability of 1.25 m. An M240 machine gun, Javelin missiles, and a sensor pedestal (with an electro-optical/infrared sensor), as well as other systems, are expected to be mounted on the vehicle. It can be transported by Lockheed Martin C-130 transport aircraft or underslung from a Boeing CH-47 transport helicopter. Other characteristics of the vehicle are presented in Table 19 (IHS Jane's, 2011).

Height:	2.56 m		**Weight:**	2.5 tons
Width:	2.24 m		**Side slope:**	>40%
Length:	4.34 m			

Table 19. MULE Characteristics (From IHS Jane’s, 2011)

f. Talon

Figure 10. Talon (From IHS Jane’s, 2011)

The Talon, developed by QinetiQ North America, is a medium-tracked multipurpose UGV in service since 2010. It has been utilized in operations in Bosnia, Afghanistan, Kuwait, Iraq, and during the September 11 attacks on the World Trade Center and the Fukishima nuclear reactor meltdown. It was used in more than 20,000 EOD missions in Iraq and Afghanistan. Around 3,000 Talon are in operation all over the world, more than any other military robot. The United States, the United Kingdom, and Australia are currently using Talon robots. It has several versions, including a second-generation Talon hazardous material (HazMat) robot for NBC detection role and an armed version called SWORDS (Special Weapons Observation Remote Reconnaissance Direct action System) (IHS Jane's, 2011).

It can perform EOD, reconnaissance, communications, sensing, security, defense, counter IED, and rescue missions and perform missions in all weather conditions and at night. It is amphibious, transportable and has a self-righting capability and long battery life. The vehicle can be controlled by an OCU with a joystick for maneuverability (IHS Jane's, 2011).

A variety of payloads can be employed, including a night-vision camera with thermal and zoom options; chemical, biological, radioactive, and nuclear (CBRN) sensor packages; counter-mine and counter-IED systems; gripper manipulator; smoke and grenade dropping modules; a breaching tool; anti-tank and light anti-tank weapon launchers; a 12-gauge shotgun; and mounts for various weapons. The Talon’s other specifications are presented in Table 19 (IHS Jane's, 2011).

Height:	0.42 m (arm stowed), 1.3 m (arm extended)	**Robot battery life:**	Up to 4.5 hours at typical operational speed with lithium ion optional battery
Width:	0.57 m	**OCU battery life:**	Up to 4 hours with lithium ion optional battery
Length:	0.86 m	**Amphibious capability:**	27 m depth
Weight:	52-71 kg, depending on mission configuration	**Video:**	Three infra-red illuminated cameras and auto-focus color zoom camera
Max speed:	8.3 km/h	**Communication:**	Digital/analogue as standard provides a 500-800 m line-of-sight range, an optional high gain antenna extends the range to 1200 m, and there is a fiber-optic cable of 300 m or 500 m length
Ground clearance:	0.07 m	**Tow capability:**	680 kg
Horizontal reach:	1.3 m	**Drag capacity:**	113 kg (with Gripper)
Payload capacity:	45 kg	**Manipulator arm:**	
Portable control station:		**Max lift capacity:**	
Length:	0.48 m	Extended:	4.5 kg
Width:	0.40 m	Unextended:	11 kg
depth:	0.22 m	**Side slope:**	45°
Weight:	15 kg		

Table 20. Talon Characteristics (From IHS Jane's, 2011)

g. Dragon Runner 20

Figure 11. Dragon Runner 20 (From IHS Jane's, 2011)

The Dragon Runner 20 (DR20), developed by QinetiQ North America, is a small wheeled or tracked reconnaissance and explosive defeating UGV in service with the U.S. Marine Corps, the U.S. Army, the U.S. Special Forces, the British Army, Special Weapons and Tactics (SWAT) squads, and the Federal Bureau of Investigation (FBI) teams (IHS Jane's, 2011).

Its various missions include reconnaissance inside buildings, sewers, drainpipes, caves and courtyards; perimeter security patrol using on-board motion and sound detectors; checkpoint security; in-vehicle and under-vehicle inspections; and hostage and barricade reconnaissance and negotiation. One person can carry a DR20 in a standard-issue pack (IHS Jane's, 2011).

Additional tracks can be mounted for mobility, and a manipulator arm with rotating shoulder, wrist and grippers can be mounted for additional capabilities. Also, a variety of disrupters can be employed with the manipulator arm. It has day and night pan/tilt/zoom cameras, motion detectors, and a listening capability that increases the unit's situational awareness (IHS Jane's, 2011).

The DR20 has field-changeable frequency capabilities that employ analog and digital radio options, standard batteries (that can be found in government inventory for the vehicle) and an easy-to-use operator-control unit. Operators can access four simultaneous camera views or any individual view. The DR20's other characteristics are given in Table 21 (IHS Jane's, 2011).

Height:	0.2 m	**Endurance:**	4-6 h
Width:	0.38 m	**Max gradient climb:**	40°
Length:	0.84 m	**Curb clearance:**	25.4 cm
Weight:	10.4 kg	**Fording depth:**	0.152 m
Max speed:	16 km/h	**Max total payload:**	9 kg
Portable control station:		**Battery type:**	XX-2590
Length:	0.55 m	**Manipulator arm:**	
Width:	0.15 m	**Max lift capacity:**	
Depth:	0.17 m	Extended:	2.27 kg
Weight:	3.17 kg	Unextended:	4.5 kg
Control link:	Radio control	**Max length:**	0.6 m
Frequency:	5 GHz	**Max grip opening:**	25 cm
Line of sight control:	600 m		

Table 21. Dragon Runner 20 Characteristics (From IHS Jane's, 2011)

h. iRobot Packbot 510 with EOD Kit

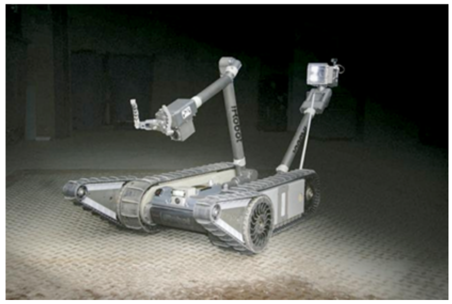

Figure 12. iRobot Packbot 510 (From IHS Jane's, 2011)

The iRobot Packbot 510, developed by iRobot Corp., is a small-tracked, explosives-defeating UGV in service with all U.S. Forces. It can be used for as bomb disposal (to identify and neutralize roadside bombs, car bombs, IEDs), checkpoints (to examine vehicles, packages and buildings in order to distinguish IEDs from harmless objects), inspections, explosives detection, and route clearance. It is able to ascend stairs and maneuver across uneven surfaces with the help of a set of polymer caterpillar tracks and an extra pair of caterpillar tracked "flippers" at one end (IHS Jane's, 2011).

It has a variety of cameras. The surveillance camera is a Charge-Coupled Device (CCD) with a 312 × zoom function with continuous pan and low-light capabilities. The operator can view forward, rear, and downward directions, as well as the manipulator position, with a wide-angle drive camera mounted on the base unit. It has two color cameras providing a view of the head from the manipulator's second elbow and the robot's position. Movement is primarily followed by the cameras on the vision and targeting head (IHS Jane's, 2011).

The iRobot Packbot 510 is controlled by a portable command console using either a radio-control system or fiber-optic cable. The portable command console has a "gamepad" style controller with a command screen that provides feeds from the robot's on-board cameras and displays sensor information. There are manipulator positions set in advance and a 3-D visualization of the robot can be displayed. The robot's other characteristics are given in Table 22 (IHS Jane's, 2011).

Height:	0.40 m (manipulator stowed), 2.21 m (manipulator extended)	**Power supply:**	2 × 30 Ah 12 V gel cell batteries on vehicle
Width:	0.40 m (flippers off), 0.52 m (flippers on)	**Manipulator system (standard):**	
Length:	0.81 m (flippers stowed), 1.01 m (flippers extended)	**Shoulder pivot:**	220°
Weight:	30.8 kg	**Elbow pivot:**	340° (elbow 1), 340° (elbow 2)
Max speed:	9.3 km/h	**Lift capability:**	
Command console:		**Full extension:**	4.5 kg
Weight:	18.5 kg (with one battery)	**Maximum:**	13.5 kg
Dimensions:	0.45 × 0.37 × 0.46 m (open)	**Reach:**	
Screen:	0.26 m, daylight readable	**Horizontal:**	2.03 m
Length:	0.48 m		

Table 22. iRobot Packbot 510 with EOD Kit Characteristics (From IHS Jane's, 2011)

i. Multifunction, Agile, Remote-Controlled Robot (MARCbot)

Figure 13. MARCbot (From IHS Jane's, 2011)

The MARCbot, developed by Exponent, is a small-wheeled explosive-defeating UGV in service with the U.S. Army (IHS Jane's, 2011). It is used to investigate suspected IED emplacements (DoD, 2009).

According to the developer, its features include:

- Remote observation distance greater than 100 meters
- Low-light camera and LED arrays providing nighttime mission capability

- Pan/tilt camera that can be raised to a height of 3 feet and tipped forward as far as 1.2 feet for viewing the tops of boxes and looking into cans and over burlap sacks

- Platform able to navigate most curbs

- Powered by military standard x90 batteries (BB-2590, BB-390) instead of expensive, proprietary batteries

- Low-cost platform intended as a disposable-type asset to address otherwise problematic technical support/logistics of complex, expensive robots

- System cost less than $10,000 USD (Exponent, n.d.)

Other characteristics of the MARCbot are given in Table 23.

Height (Camera Arm Retracted):	34.2 cm		**Weight:**	11.3 kg
Width:	48.3 cm		**Ground Clearance:**	10 cm
Camera height (extended):	61 cm		**Pan/Tilt Camera:**	Fixed-focus, high-resolution, Low-Lux, color camera
Camera forward projection (extended):	35.6 cm		**Operator control unit:**	
Max Camera Arm Height:	61 cm		**Weight:**	3.9 kg

Table 23. MARCbot Characteristics (From Exponent, n.d.)

j. Recon Scout Throwbot

Figure 14. Recon Scout Throwbot (From IHS Jane's, 2011)

According to IHS Jane's (2011), the Recon Scout Throwbot, developed by Recon Robotics, is a small-wheeled under-vehicle inspection and reconnaissance UGV. It is in service with the U.S. military, the FBI, some U.S. police, several governmental departments in the U.S., as well as the UK police and military. It has several versions, including an under-vehicle inspection version (UVI), an infrared version (Recon Scout IR), an extra-terrain version (Recon Scout XT), and the Recon Scout Rescue version (IHS Jane's, 2011).

The role of the vehicle is a stealthy reconnaissance first-responder or "first-in" system for hostage and military scenarios. It is a small and quiet robot that it is 7 cm high and has a noise level of 20 dB. It is durable robot and can be thrown from a distance of greater than 31 m, or dropped from a height of greater than 9.1 m. It can be activated in ten seconds by removing the pin from the robot and turning on the OCU. The OCU can be operated with one hand (IHS Jane's, 2011).

With its black-and-white image sensor, the operator can see a 60° view immediately and a 360° view in five seconds. A Command Monitoring Station kit (consisting of a high-gain antenna with tripod and mount, a video-receive module, cables and software) can increase the operating range by more than 300 meters. The other characteristics of the robot are given in Table 24 (IHS Jane's, 2011).

Height:	0.07 m		**Portable control station:**	
Width:	0.18 m		Length:	0.52 m
Length:	0.07 m		Width:	0.08 m
Weight:	0.54 kg		Depth:	0.03 m
Max speed:	1.18 km/h		**Weight:**	0.79 kg
Turning circle:	Zero		**Line of sight control:**	30 m (indoor), 91 m (outdoor)

Table 24. Recon Scout Characteristics (From IHS Jane's, 2011)

2. United Kingdom

a. Cutlass

Figure 15. Cutlass on EOD Operations (From IHS Jane’s, 2011)

According to IHS Jane’s (2011), the Cutlass, developed by Remotec, is a medium-wheeled EOD UGV used by the UK Ministry of Defense (MoD) for anti-terrorism operations. It has a modular design with the latest technology that can employ a variety of payloads, sensors, and tools. Its state-of-the-art gripper on the manipulator arm allows greater movement and agility inside limited spaces, like the interior of a car. It can move at slow speeds, yet accelerate fast for different sorts of operations, and it can operate in all weather conditions and all types of hard and soft terrain with its six-wheeled articulated design. The other characteristics of the vehicle are given in Table 25 (IHS Jane's, 2011).

Height:	1.27 m
Width:	0.72 m
Length:	1.24 m
Weight:	417 kg
Max speed:	13 km/h
Curb clearance:	0.12 m
Fording depth:	0.50 m
Obstacle clearance:	0.30 m
Control link:	Radio control (up to 1 km) or fiber-optic cable (up to 500 m)

Power supply:	Lithium ion, nominal 40 V complete with battery management system
Number of cameras:	6, with picture-in-picture
Manipulator arm:	
Max lift capacity:	
Extended:	2.27 kg
Unextended:	4.5 kg
Max length:	0.6 m
Max grip opening:	25 cm

Table 25. Cutlass Characteristics (From IHS Jane’s, 2011)

b. *MACE Series of Vehicles*

Figure 16. MACE 3 (From MIRA, n.d.)

The MACE series of vehicles are large-wheeled multipurpose UGVs. The MACE 1 won the "Best Use of Autonomy" award at the UK MoD's Grand Challenge in 2008. The development of the MACE 2 and 3 is ongoing (IHS Jane's, 2011). The MACE 3 has command and control systems, as well as autonomous systems that were developed on the MACE 2 (MIRA, n.d.).

A non-line-of-sight (N-LOS) control station on the MACE 2 allows the vehicle to be operated from a distance up to 5 km. The MACE 2 has tele-operational or semi-autonomous modes with on-board intelligence consisting of waypoint following, local obstacle avoidance, and haptic feedback. Cameras, on-board vehicle diagnostics, and GPS data contribute to the situational awareness of the operator (IHS Jane's, 2011).

According to the developer, the MACE 2 has the following basic features:

- Light-weight tubular frame with excellent torsional rigidity properties
- Centrally-mounted TD4 100kw turbo-diesel engine with auto transmission
- Distributed UGV control architecture employing MIRA Functional Safety Strategy

- One-ton payload capability
- Improved medium mobility terrain performance
- 80 km/h maximum speed (MIRA, n.d.).

The other specifications of MACE 2 are given in Table 26.

Height:	1.3 m	**Weight:**	1,200 kg
Width:	1.8 m	**Endurance:**	193 km
Length:	1.65 m	**Curb clearance:**	26 cm
Portable control station:		**Max gradient climb:**	45°
Length:	0.50 m	**Turning circle:**	2.5 m
Width:	0.35 m	**Fording depth:**	0.75 m
Depth:	0.20 m		
Weight:	5 kg		

Table 26. MACE 2 Characteristics (From IHS Jane's, 2011)

According to MIRA (2011), the MACE 3 has tele-operational and autonomous modes. It can perform load carriage and perimeter protection mission and also be used to counter IEDs. Its basic features are:

- Land Rover Defender chassis (all wheel base variants)
- Driver position maintained if required
- Distributed UGV control architecture employing MIRA functional safety strategy
- Two-ton payload capability
- Medium mobility terrain performance
- 50 km/h maximum speed (MIRA, n.d.).

3. Canada

a. GRUNT

Figure 17. GRUNT (From IHS Jane's, 2011)

The GRUNT (GRound UNiTs), developed by Frontline Robotics, is a medium-wheeled patrol and surveillance UGV used by Canada and South Korea. A Mobile Autonomous Guard System (MAGS), including two GRUNTs that based on the Argo All-Terrain-Vehicle, a base station command and control system, and a complete software development environment were delivered to South Korea in 2005 by the developer. The vehicles included COTS sensors and the PC-104 industrial computer (IHS Jane's, 2011).

The GRUNT can perform perimeter security checks and surveillance of critical infrastructure. It is an autonomous UGV that has radio communication systems, all-around imaging cameras, night-vision sensors, radar, and a continuous navigation system (IHS Jane's, 2011).

A Frontline Robotics' Team Intelligence software platform, named Robot Open Control (ROC), enables fully autonomous operation and decision-making collaboration between GRUNTs. They can work together to identify an intruder and disturb and prevent intrusion, and they can observe security threats and communicate with personnel staying in a safe place. Other characteristics of the vehicle are presented in Table 27 (IHS Jane's, 2011).

Height:	1.91 m	**Max gradient climb:**	15°
Width:	1.52 m	**Curb clearance:**	25 cm
Length:	2.79 m	**Turning circle:**	2.79 m
Weight:	450 kg	**Line-of-Sight control**	2,000 m
Max speed:	30 km/h	**Frequency**	2.4 GHz
Endurance:	Varies depending on mission	**Navigation System**	GPS, INS, FOG, magnetometer, odometry
Max total payload:	771 kg		

Table 27. GRUNT Characteristics (From IHS Jane’s, 2011)

4. Israel

a. Guardium

Figure 18. Guardium (From IHS Jane’s, 2011)

According to IHS Jane’s (2011), the Guardium, developed by G-NIUS Unmanned Ground Systems LTD, is a large-wheeled patrol UGV in service with the Israel Defense Force (IDF). It was tested by Israel's Airport Authority in 2008, and the IDF has been deploying Guardiums along the Gaza border since 2011 (IHS Jane's, 2011).

It can perform specialized missions including convoy security, reconnaissance, surveillance, and combat logistic support as well as regular missions like programmed patrols along border routes (G-NIUS Unmanned Ground Systems, n.d.; IHS Jane’s, 2011). In addition, it can autonomously respond to unscheduled events following a set of guidelines programmed especially for the site characteristics and security doctrine (G-NIUS Unmanned Ground Systems, n.d.).

The vehicle has payload that include a day/night camera, communications intelligence and electronic support-measures systems, a metal detector, and a communications/observation mast. The vehicle has a high-level of self-control (it can set its own route and overcome obstacles), and Guardiums can work together within a network (IHS Jane's, 2011).

According to the developer, the vehicle has the following characteristics:

Vehicle Level

- Autonomous mission execution
- Real-time, self-ruling, obstacle’s detection and avoidance
- Proven safety system
- Superb off-road maneuverability

System Level

- Easy to operate, dedicated command & control application in complementary operational versions: stationary, mobile and portable
- Built-in debriefing and training capabilities
- Variety of customer tailored wireless communication solutions

Mission Level

- Modular selection of payloads for comprehensive situational awareness and different mission requirements: EO/IR camera, Radar, Remotely Operated
- Weapon Systems, Non-lethal Weapon Systems
- Electronic Counter Measures, COMMINT, Hostile Fire Indicator (HFI), two-way audio link, CBRN sniffers, RFID Interrogator, fire extinguishers and more

- Stationary, Mobile and Portable control terminals (G-NIUS Unmanned Ground Systems, n.d.)

The Guardium's other specifications are given in Table 28.

Height:	2.2 m	**Endurance:**	24 hours and up to days of continuous operation
Width:	1.8 m	**Max total payload:**	300 kg
Length:	2.95 m	**Turning circle:**	Platform dependent
Weight:	1,400 kg	**Power Plant:**	Heavy and standard fuels' engines are available
Max speed:	50 km/h (in semi-autonomous mode)		

Table 28. Guardium Characteristics (From G-NIUS Unmanned Ground Systems, n.d.; IHS Jane's, 2011)

5. France

a. Cameleon

Figure 19. Cameleon (From IHS Jane's, 2011)

The Cameleon, developed by ECA Robotics, is a small-tracked multipurpose UGV used by France that can perform missions including counter-IED, EOD, route clearance, reconnaissance, first response, survey, mapping, and hazardous material operations. The following can be mounted on its manipulator arm: a gripper color camera with x40 zoom, a turret that has a color day/night camera with x4 zoom, a disruptor camera with lighting, and a chemical and radiological detector (IHS Jane's, 2011). The robot has other payloads that include a navigation module, sound detection, a telescopic observation video camera, a smoke dispenser, gas and tears launchers, indoor localization and mapping, and dropping charge (ECA Robotics, 2011; IHS Jane's, 2011).

According to ECA Robotics (2011), piloting aid features include pre-determined manipulator arm movements, SLAM cartography, indoor/outdoor localization, and a follower/leader module. Open architecture is dependent upon a Multi-Agent System (MAS) that enables plug and play mission modules (ECA Robotics, 2011).

The working range of the robot is up to 300 m with radio, but this can be extended 100 m on demand and up to 200 m with fiber-optic cable (ECA Robotics, 2011). The command and control unit has a 26.4 cm touchscreen and two joysticks. The other characteristics of the robot are given in Table 29 (ECA Robotics, 2011; IHS Jane's, 2011).

Height:	0.19 m		**Max gradient climb:**	35°
Width:	0.50 m		**Curb clearance:**	0.25 m
Length:	0.67 m		**Turning Circle:**	Zero
Weight:	25 kg		**Max payload:**	20 kg
Max speed:	6 km/h		**Battery:**	Lithium ion, 32 V
Endurance:	2.5 h		**Manipulator arm:**	
Portable control station:			**Max lift capacity:**	
Length:	0.23 m		Extended:	3 kg
Width:	0.40 m		Unextended:	8 kg
Depth:	0.65 m		**Max length:**	1.5 m
Weight:	3.2 kg		**Weight:**	15 kg (without accessories)
Frequency:	2.4 GHz		**Gripper:**	360° rotation, 90° aperture

Table 29. Cameleon Characteristics (From ECA Robotics, 2011; IHS Jane's, 2011)

6. Germany

a. tEODor

Figure 20. tEODor (From IHS Jane’s, 2011)

According to IHS Jane’s (2011), the Telerob Explosive Ordnance Disposal and observation robot (tEODor), developed by Telerob, is a medium-tracked EOD UGV. More than 41 countries have bought at least 380 of these robots in the past decade (IHS Jane's, 2011).

The key role of the robot is remote-controlled bomb disposal. It has a universal interface, allowing employment of standard ballistic systems, and 40 standard tools and devices can be used with the robot. The tEODor can employ up to five ballistic systems in parallel, with a maximum of 10 individual rounds. Aquaset, TEL220, the Remington 11-87 shotgun, Dynergit, Telemach, drills, grinders, laser aiming devices, window breakers, and various camera systems can all be used with the robot. The robot can operate in ambient temperatures ranging from -20 to +60°C. It has an integrated diagnostics system, which has a remote maintenance module used for easy analysis and the elimination of errors. The robot’s other specifications are presented in Table 30 (IHS Jane's, 2011).

Height:	1.1-2.8 m		**Cameras:**	4 color cameras with lighting
Width:	0.68 m		**Control:**	Radio control up to 1 km distance, optional fiber-optic cable control
Length:	1.3 m		**Manipulator arm:**	
Weight:	375 kg		**Max lift capacity:**	
Max speed:	3 km/h		Extended:	100 kg
Max payload:	350 kg		Unextended:	20 kg
Turning circle:	1.46 m		**Max reach:**	1.8 m
Battery:	Lithium ion		**Tower rotation:**	±205°
Towing capacity:	3,000 N		**Upper arm incline:**	+144°, -85°
Scope:			**Lower arm incline:**	±110°
Vertical:	2.8 m		**Lower arm extension:**	39 cm
Horizontal:	2.3 m		**Gripper incline:**	+120°, -95°
Beneath vehicles:	1.25 m		**Gripper rotation:**	Continuous
Electromagnetic compatibility (EMC)	EN 55022 B EN 61000-4 part 2, 3, 4 and 6 better than 30 V/m		**Gripper width:**	30 cm
Telescopic arm	0-0.4 m		**Gripper force:**	600 N

Table 30. tEODor Characteristics (From IHS Jane's, 2011)

III. UGVS WITHIN THE TURKISH MND

A. INTRODUCTION

The founder of the Republic of Turkey, Mustafa Kemal Atatürk, applied his intellect and abundant vision to the core values of the state, and Turkey, as a growing country, has remained a secular, western-oriented country since 1923. After its foundation, Turkey increased its efforts in international affairs and joined the United Nations (UN) in 1945 and NATO in 1952. The geostrategic location of Turkey was the main factor in its growing relationship with western countries, especially with the U.S., during the Cold War era. Turkey was one of only two NATO countries (the other was Norway) that had a common border with the Soviet Union. The Turkish Armed Forces was the second largest in NATO (after the U.S.), and its capability was a significant deterrent to the Soviet Union. Furthermore, Turkey controls two straits, the Bosporus and Dardanelles, which provided the only available passage to warm waters for the Soviet Union's fleet. These factors helped improve U.S.-Turkey relations. The Republic of Turkey has generally proven to be a valuable and steadfast U.S. ally (Robey & Voldermark, 2004).

The Turkish-United States military and security assistance relationship is an important area of cooperation. The United States has provided nearly $13.8 billion in overall military assistance to Turkey since 1948. Turkey has increased its economic growth and military self-sufficiency during the last two decades, so most of the aid has been discontinued. Current annual military and security assistance can be seen Table 31 (U.S. Library of Congress, 2011).

Fiscal Year(s)	Foreign Military Financing (FMF)	Excess Defense Articles	International Military Education and Training (IMET)	Nonproliferation, Antiterrorism, Demining and Related Programs (NADR)	International Narcotics Control and Law Enforcement (INCLE)	Other Grants	Total Grants	Loans
1948-1975	-	869.0	111.8	-	-	3,406.0	4,386.8	185.0
1976-1981	-	-	3.4	-	1.0	10.5	14.9	952.9
1982-1992	1,884.0	-	36.4	-	6.7	1,362.1	3,289.2	2,769.1
1993-2001	-	205.1	14.0	0.1	3.2	-	222.4	1,678.1
2002-2008	170.0	21.1	23.7	8.6	0.1	-	223.5	-
2009	1.0	-	3.2	1.9	0.5	-	6.6	-
2010	-	-	5.0	3.0	-	-	8.0	-
2011 Request	-	-	4.0	1.4	0.5	-	5.9	-
2012 Request	-	-	4.0	-	0.5	-	4.5	-
TOTAL	**2,055.0**	**1,095.2**	**205.5**	**15.0**	**12.5**	**4,778.6**	**8,161.8**	**5,585.1**

Table 31. U.S. Military and Security Assistance to Turkey (Historical $ in millions) (From U.S. Library of Congress, 2011)

U.S.-Turkey defense cooperation continues in the areas of increasing stability in the region and counter terrorism. In support of the War on Terrorism, Turkey wants to strengthen its Armed Forces by acquiring advanced military equipment from the U.S. government and private sector. It has sought to purchase UAVs from the U.S. since 2008 for the purpose of increasing its effectiveness in operations against terrorists by using advanced aerial vehicles. The success of these vehicles in Afghanistan is a significant consideration. According to *Jane's Sentinel Security Assessment*, Turkey requested purchase of 10 U.S.-produced MALE drones, four Predators and six Reapers (U.S. Library of Congress, 2011). On the other hand, research and development (R&D) and prototype production processes in the Turkish defense industry are ongoing, and robotic systems are the current trend in the Turkish MND. According to yearly reports, there is an increasing interest in UGVs. Therefore, in this chapter, UGV efforts will be explored within the technology management strategy of the Turkish MND – after first providing a background of the Turkish Defense Industry.

B. THE TURKISH MND

1. History of the Turkish Defense Industry

The Ottoman Empire acquired and began to use gunpowder technology shortly after it was invented. Empire employed this technology to produce powerful cannons, used for the first time in a battle against the Karamanid dynasty, one of the Anatolian Beyliks and one of the most powerful states in Anatolia from the 13th century to 1487. Between 1450 and 1550, the Ottoman Empire had the best cannon systems in the world, in terms of technological proficiency and application skills. European states did not reach the level of this technology of the Ottoman Empire until the 17th century. Establishing armories in different cities to support battles, the Empire had more than ten armories throughout its territory (Beyoğlu & Kılıç, 2010).

It also made great progress in the maritime arena. In 1081, the first Turkish fleet (50 vessels of 33 sailing ships and 17 oar ships), was constructed in the Smyrna shipyards under the order of Caka Bey, the first Turkish Commodore. During the 16th and 17th centuries, the Ottoman Empire had 140 shipyards (from the Suez Canal to the Danube, and from the Black Sea to Algeria) supporting a nearly 4,000-vessel fleet. In that era, this sea power provided sovereignty for the Ottoman Empire in the Mediterranean. After the 17th century, in spite of other advancements, technological progress in the western countries weakened the power and influence of the Ottoman Empire, and its Armed Forces became dependent on the European states in terms of technology, engineering, labor, and training (Beyoğlu & Kılıç, 2010).

During the first years of the Republic established in 1923, there was no substantial defense-industry infrastructure. However, small-scale facilities producing light guns, pistols, and ammunition contributed to victory in the Independence War. Mustafa Kemal Ataturk, founder of the Republic of Turkey, declared that Turkey must develop its defense industry and sustain its economic growth, particularly in the private sector of business. From this standpoint, during the 1920s and 1930s, the government made ventures to establish a solid defense industry infrastructure, especially in the weapon, ammunition, and aviation sectors. During the first decade of the Republic, industrialization was the policy focus of the government, and the defense industry was an indispensable part of this policy. Throughout this period, the Turkish Defense Industry reached its level of capacity producing aircraft. During the first 22 years of the Republic, a total of 17 facilities, including factories and shipyards, were set up, and a total of 112 aircraft (including 15 German-patented Junkers A-20s, 15 U.S.-patented Hawk combat aircraft, and 15 Gotha communication aircraft) had been produced in the factories by 1939 (Beyoğlu & Kılıç, 2010).

World War II changed the political environment and power balances of the world. Turkey faced the spread of Soviet communism and became the focus of other countries, such as the United States and England. Monetary support under the Marshall Plan from the United States made a significant impact on the strengthening of the Turkish Armed Forces and increasing its deterrence against the Soviet threat. This support was provided as a donation; however, the maintenance cost to support the strengthened forces created a heavy burden on the Turkish budget. As a consequence, the new defense-industry infrastructure began to disappear: demand in the market began to decrease, so the factories lost their efficiency (Beyoğlu & Kılıç, 2010).

Within their problematic region, Turkey faced crises during the 1960s. Events of the time, including President Lyndon Johnson’s letter of 1964, the Cyprus crisis, the Cyprus Peace Operation in 1974, and the subsequent U.S. embargo against Turkey, all significantly affected the policy of the Turkish defense industry. It clarified without doubt that the national defense industry was vital to eliminating dependence on the defense industries of other states and to providing required material and systems to the Turkish Armed Forces. The development of a defense industry based on national resources was a necessity. In 1974, the Turkish Armed Forces Foundation was established with this understanding in mind, and several investments, though limited, were initiated. As a result, six defense companies were established between 1945 and 1975, and 25 new defense companies (among them some of the biggest defense companies in Turkey today) were established between 1975 and 1990 (Beyoğlu & Kılıç, 2010).

The acquisition methods used by the Turkish MND were to both receive used MDSs as donations and procure MDSs as required. Foreign Military Sales and donations from Germany were two common sources in the procurement of MDSs. This procurement method was used until 1985, when the Under Secretariat for Defense Industries (SSM) was established. At that time, the Turkish MND significantly changed its defense acquisition strategy, a shift that also facilitated the procurement of modern MDSs for the Turkish Armed Forces. Since the establishment of the SSM, private investments in the defense industry have increased. With the new acquisition strategy, the initial step was to establish joint ventures with foreign corporations. In the resulting projects, systems and sub-systems were manufactured under licensed contracts. The co-production of the F-16 fighter aircraft was the first attempt to use this new strategy. Since the 2000s, the strategy has been updated because the establishment phase of the Turkish Defense Industry was completed. Today, the Turkish defense industry is maturing and has enough capacity to compete on the same scale as other defense industries by producing defense systems with unique designs. Figure 21 shows the progress of the defense industry based on acquisition strategy and number of projects (Beyoğlu & Kılıç, 2010).

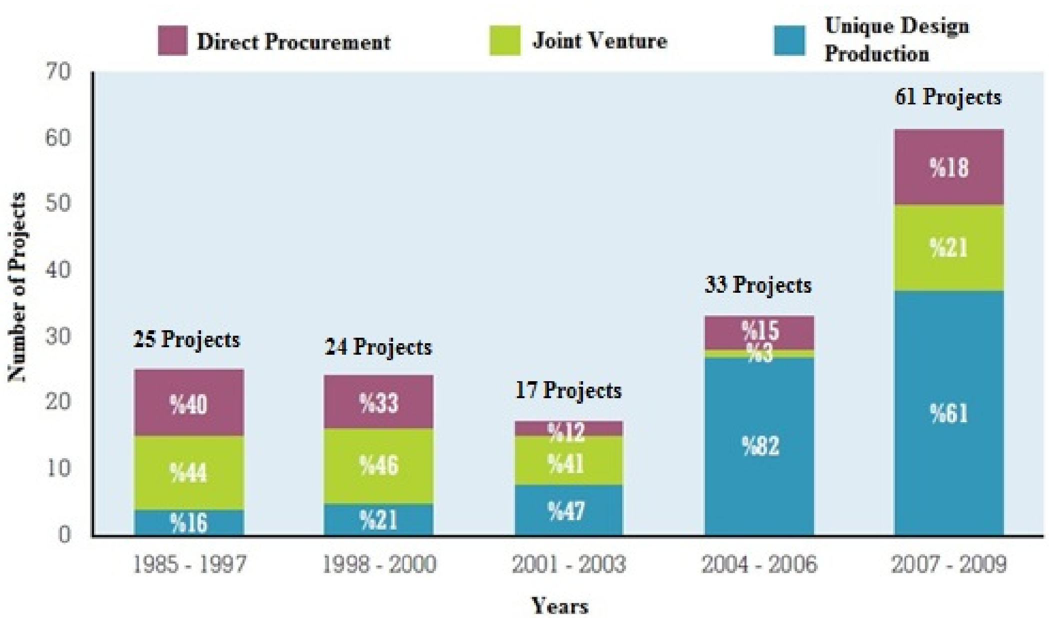

Figure 21. The Progress of the Defense Industry Based on Acquisition Strategy and the Number of Projects. (From Beyoğlu & Kılıç, 2010)

Figure 22 shows the progress of the defense industry based on acquisition strategy and contract price.

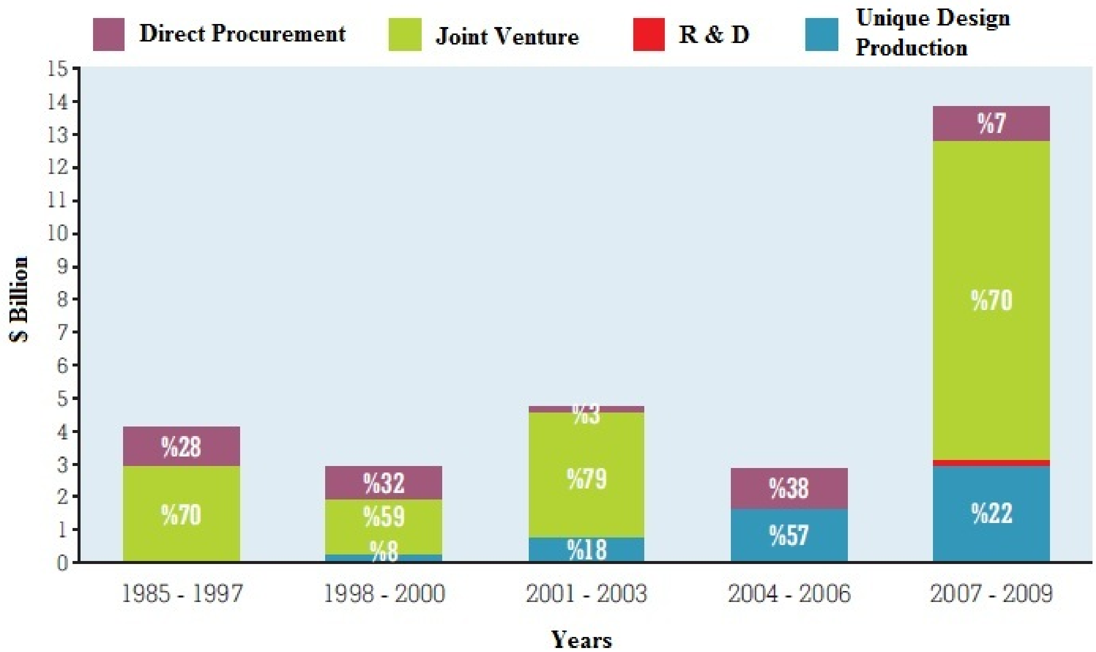

Figure 22. The Progress of the Defense Industry Based on Acquisition Strategy and Contract Price. (From Beyoğlu & Kılıç, 2010)

2. The Under Secretariat for Defense Industries (SSM)

The SSM was established in 1985. According to Law: 3238, it has two fundamental responsibilities: the modernization of the Turkish Armed Forces and the development of the Turkish defense industry. The SSM is the most important stakeholder in the Turkish desire for an indigenous defense industry. Capability in this field would make Turkey less susceptible to foreign pressure in the future. Furthermore, its other desire is to transition from being solely a buyer in the defense market to becoming an exporter of defense articles and services to other developing nations (Robey & Voldermark, 2004).

According to the SSM Strategic Plan 2007-2011 (2007), the vision of the SSM is “to be the procurement authority leading the Turkish defense industry to be competitive, integrated with the international market and able to introduce unique indigenous solutions in accordance with technological improvements to meet national strategic defense and security requirements” (p. 1).

The mission of the SSM is “to meet the system requirements of the Turkish Armed Forces and those government organizations promote the national defense and security; to establish and implement strategy and procedures for the development of the defense industry” (SSM, 2007, p. 1).

SSM’s values are:

- Authority: An authority in defense industry project management
- Capability based: Employed with competent and team-oriented staff
- Transparent: Open to audit and supervision
- Reliable: Ethically organized culture
- Innovative: A dynamic organization, open to change and improvement
- Objective: Decisions based on objective facts and analytical methodologies
- Stakeholder oriented: Service based on expectations and needs (SSM, 2007, p. 1)

The success of the SSM depends on the balance between the modernization of the Armed Forces and the development of the Turkish defense industry. The most timely, effective, and efficient method to meet the needs of the Turkish Armed Forces is to acquire off-the-shelf products or systems which are already certified. However, this method creates hurdles in the development of an indigenous defense industry (Bayar, 2010).

On the other hand, acquiring these products and systems from the indigenous defense industry will likely mean that Armed Forces will not have them in a timely manner. The SSM tries to balance these two significant factors in its strategies. In 2010, Murad Bayar, the Undersecretary for Defense Industries, evaluated the first 25 years of the SSM in the periodical *Savunma Sanayii Gündemi*, in describing the current situation of the Turkish Defense Industry along the following lines:

- The Turkish Defense Industry has reached the capability to develop and manufacture most of the major defense systems needed by the Turkish Armed Forces. The projects are planned as indigenous defense-industry programs in the initial phase of the acquisition process and the percentage of direct procurement from other countries is below 10%.
- The Turkish Defense Industry is the biggest investor in the industries in spending over $500 million on R&D.
- There are over 100 companies in the defense industry, and one of these is in the list of the top 100 defense industry companies in the world.
- The export level of defense articles is very close to $1 billion, an important goal for a defense industry. It means that the armed forces of some other countries have begun to use ground or sea systems and electronic devices made by Turkey.
- The Turkish Defense Industry made progress in integration with supplier companies and Small and Medium Sized Enterprises (SME) which produce unique design work or subparts of a defense system.
- Universities and R&D centers are included to the R&D projects of the defense systems. Today, over 20 universities are working on future defense technologies (Bayar, 2010).

In the near future, the goals of Turkish Defense Industry are:

- To complete the development and manufacture of such main defense systems as a Tactical Reconnaissance and Attack Helicopter (ATAK), a Turkish National Main Battle Tank (ALTAY), a Patrol and Anti-Submarine Warfare Ship (MILGEM – Milli Gemi – National Ship), UAV (ANKA), an Observation Satellite (GOKTURK), and an Air and Missile Defense System

- To develop and manufacture a national indigenous infantryman combat rifle
- To increase the number of companies from 1 to 3 on the list of the first 100 defense industry companies in the world
- To develop and manufacture articles which can compete with those same articles made in other countries
- To increase cooperation with universities and R&D centers in order to strengthen the technology infrastructure of the industry (Bayar, 2010)

In the long run, the goals of the Turkish Defense Industry are:

- To design, develop, and manufacture a national indigenous combat and training aircraft
- To be in the top 10 defense industries in the world
- To make progress in the technology development infrastructure (Bayar, 2010)

The Turkish defense industry completed the first phase, establishment, in 25 years. Moving forward, a professional approach should be used to reach its goals. Technology management strategy is an important part of this approach (Bayar, 2010).

C. TECHNOLOGY MANAGEMENT STRATEGY OF THE TURKISH MND

1. Overview

International competition has triggered a race for technological superiority in military applications. Nowadays, MDSs are being manufactured with the latest technologies. Some new technologies in the civil sector have been swiftly implemented in military systems. Therefore, the main focus for defense and security has switched to technological and information superiority, a subject that should take a central place in strategic plans (Bayar, 2010).

According to its Strategic Plan 2007-2011 (2007), the SSM's priorities are Procurement Management, Industry and Technology Management, International Cooperation, and Organizational Development. The strategic goals of the SSM are:

Strategic Goal 1: To Improve Procurement Activities in Accordance with User Requirements and Industrial Goals

- In order to enhance procurement management capability, project management processes will be improved.
- In accordance with achieving user satisfaction, project cycle times (duration between kick-off and contract awarding) will be shortened.
- Quality, test and certification activities will be improved and made timely and effective.
- Decisions made in project management will be consistent with institutional strategies.

Strategic Goal 2: To Restructure the Defense Industry to Provide Unique Local Solutions and Compete in the International Arena

- Indigenous share in expenditures for Turkish Armed Forces' defense equipment expenditures shall be enhanced.
- Activities that ensure sustainability and improve efficiency in the local defense industry will be actualized.
- Integration of SME's and supplier companies to defense industry shall be enhanced.
- It shall be ensured that R&D Roadmap and Network of Excellences' operate effectively.

Strategic Goal 3: To Participate Actively in Multinational Defense and Security Projects that Promote International Cooperation

- By fostering specialization and encouraging local industry to take its place in the international supply chain, strategic cooperation efforts will be promoted.

- Turkish industry’s share in NATO defense projects shall be increased.
- Export of defense and aeronautics products will be promoted and supported.

Strategic Goal 4: To Improve the Organizational Structure

- The Strategic Human Resources Program will employ highly qualified staff to provide necessary training, and a productive environment to maintain organizational loyalty.
- Knowledge and performance based management approach and strategic management systematic shall be institutionalized.
- Governance and security of information produced and the sharing of knowledge will be improved. (SSM, 2007, p. 2)

By setting strategic goal 2, the Turkish MND put an emphasis on the technological infrastructure of the Turkish Defense Industry and issued its Technology Management Strategy 2011-2016. In this section of the study, we will explore the main lines of this strategy – with a focus on UGV efforts in it and in the defense industry.

2. Technology Management Strategy of the Turkish MND

The procurement percentage through the indigenous defense industry for the needs of the Turkish Armed Forces has reached 46%. However, dependence on the defense industries of other states continues for some critical sub-systems, components, and technological infrastructure. Turkey has experienced problems with the expansion of its technological infrastructure because of foreign government policies and restrictions. In order to solve these problems, the Turkish MND needs R&D projects focused on new technologies, which will make the purchase of systems from the indigenous defense industry a maintainable strategy (SSM, 2011).

On the other hand, the Turkish MND must also plan and develop R&D projects that are focused on products that will meet the demands of the Turkish Armed Forces in the near future. From this standpoint, the technology management strategy of the Turkish

MND is focused on the needs of the Turkish Armed Forces and the technology infrastructure of the defense industry, taking into consideration competition and maintainability. It includes four main areas: new technology acquisition activities, R&D projects, a technology acquisition roadmap, and networks of excellence. To accomplish its technology management strategy, the SSM has a directive and promotional authority over the defense industry. Three significant criteria must be taken into consideration in the study of technology management, which has a product-focused approach in order to meet the needs of the Turkish Armed Forces. These criteria are:

- Compliance with the needs and goals of the projects
- Expansion of the technology infrastructure for future technologies
- Cooperation among industry, universities, R&D institutions, and SMEs (SSM, 2011)

In the last decade, the prime contractor model has been used in MDS contracts. Within this model, illustrated in Figure 23, projects have been spread to the base (SSM, 2011).

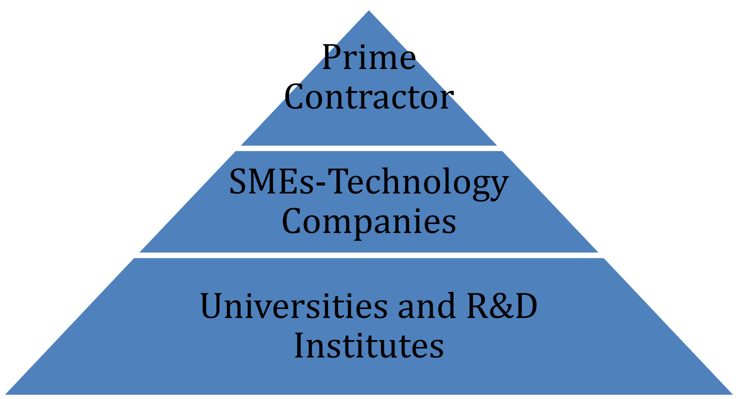

Figure 23. Prime Contractor Model (From SSM, 2011)

In this model, large scale companies in the industry are the lead system integrator. SMEs and technology companies have responsibility for the development and production of the sub-systems and components. Universities and R&D agencies have responsibility for research in the basic and applied sciences and expanding the technology infrastructure of industry for the required new technologies (SSM, 2011).

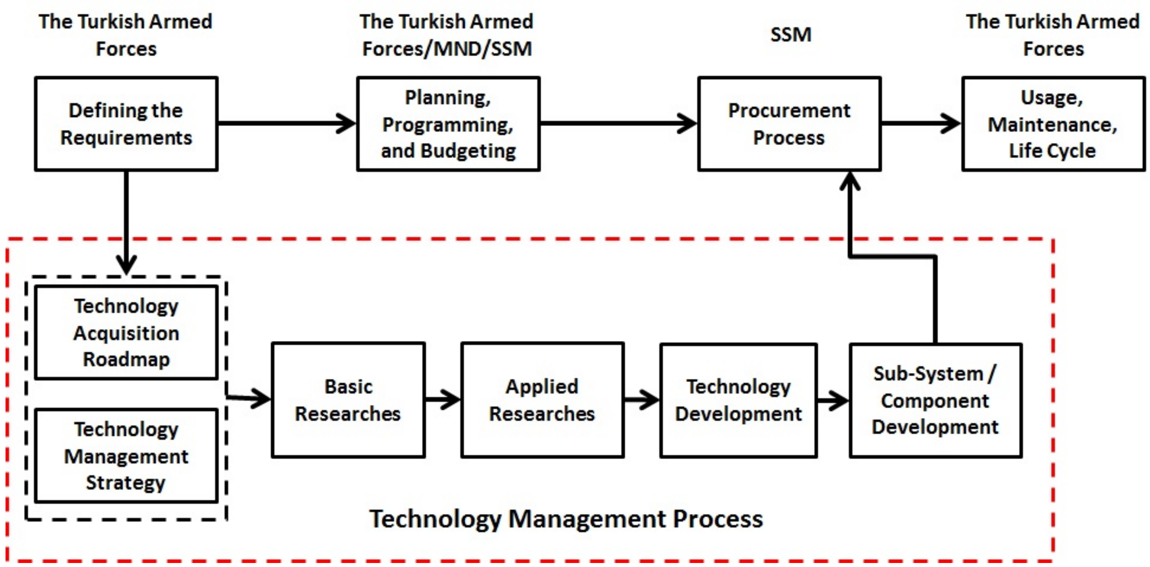

Figure 24. Technology Management Process (From SSM, 2011)

As Figure 24 shows, the R&D process is configured independently from the acquisition process but is also parallel to it. R&D studies have been initiated to define requirements. They establish a base for projects, which will then be procured from the indigenous defense industry. With this approach, not only are the needs of the Turkish Armed Forces regarding timely MDS procurement satisfied, the technology infrastructure of the Turkish defense industry also expands. The critical sub-systems, components, and technologies are all handled in the technology acquisition roadmap. After the needs of the Turkish Armed Forces are defined, area specialists clarify the requirements. Throughout all of these processes, cooperation and knowledge sharing among the industry, universities, R&D agencies, and the SSM (defined as "Networks of Excellence") are the fundamentals of this strategy (SSM, 2011).

According to the technology acquisition roadmap, after the needs and the requirements of the Turkish Armed Forces are defined, the sub-systems, components, and related technologies are identified in order to expand the technology infrastructure of the defense industry (SSM, 2011). The practical method of the technology acquisition strategy is as follows:

- System, sub-system, component, and related technology areas of a project will be defined and updated according to new technologies.

- The capabilities, infrastructure, and incompetence in the sub-systems, components, and related technology areas will be determined.

- Incompetent areas will be prioritized for attention.

- According to the prioritization, an umbrella project will be defined to gain competence.

- Network of Excellence will be used in this umbrella project. (SSM, 2011, p. 22)

According to the Technology Management Strategy 2011–2016 (2011) of the SSM, twelve technology areas have been selected to expand the technology infrastructure of the Turkish defense industry. The studies are going on within the Network of Excellence. The twelve technology areas are as follows:

- Autonomous Behavior
- Advanced materials
- Space
- Energy and propulsion technologies
- Sensors
- Modeling and Simulation
- Electronic Warfare
- Rocket, Missile, Torpedo, Mine technologies
- Communication
- Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR)

- CBRN Technologies
- Micro and Nano Technologies (SSM, 2011, p. 31)

The universities, R&D institutes, and SMEs in Turkey continue their studies and research efforts in these twelve technology areas.

3. UGV Efforts in the Turkish MND

Today, UAVs have proven their performance and success in the operational area, and many countries have increased investment in unmanned systems. Turkey is one of these countries. In Turkey, the initial interest related to robotics systems was in UAVs. The Turkish MND has initiated studies related to Autonomous Behavior technologies to develop an industry technology base—because of the potential benefits of UAVs in the operational area. In its Technology Management Strategy, the SSM has identified primary technology areas which will be developed under the Network of Excellence method. These areas include Autonomy, Artificial Intelligence, and Command & Control and Communication technologies (SSM, 2011). Furthermore, according to its 2010 Yearly Activity Report (2010), the SSM signed contracts for the urgent UAV needs of the Turkish Armed Forces. At the same time, the SSM signed R&D and design contracts to improve its defense technology infrastructure (SSM, 2010).

On the other hand, while there is a growing interest in UGVs, there are no signed contracts or activities for UGVs (SSM, 2010). Conceptual studies and research efforts in supporting technology areas are ongoing.

4. UGV Efforts in the Turkish Defense Industry

According to the Technology Management Strategy 2011-2016 (2011) of the SSM (and in parallel with technological progress in the rest of the world), Turkish defense companies are investing in the infrastructure of unmanned systems to improve capabilities in that area. They are trying to expand their supporting technology and know-how infrastructure. The leading company in this research is ASELSAN, which has conducted research on two concept UGVs produced for homeland security purposes. Their areas of emphasis are patrol, surveillance, and reconnaissance. Alper Erdener, ASELSAN's lead systems engineer for unmanned systems, pointed out that the Multi Autonomous Ground-robotic International Challenge (MAGIC) 2010 competition[4] (co-sponsored by the U.S. Department of Defense and the Australian Ministry of Defense), was key to developing the new systems' autonomous capabilities (Williams, 2011).

UGVs produced by Turkish defense companies are analyzed below in order to determine the current UGV capabilities of the Turkish defense industry.

a. Izci

Figure 25. Izci (From IHS Jane's, 2011)

Izci, meaning "Scout," is a medium-wheeled reconnaissance and patrol UGV developed by ASELSAN. It has a modular design, so it is suitable for a wide range of missions, such as asymmetric warfare, border surveillance, homeland security, logistics, perimeter patrol of high-value installations, observation, and reconnaissance. There are two options for controlling the UGV: drive-by-wire and remote control. The Izci has a 4 x 4 commercial all-terrain chassis. Advanced electronic systems have been used in development. They enable user waypoint navigation, avoidance and path-following (under day/night and various weather conditions), obstacle detection, and secure data and video transmission. A low-profile, mast-mounted, two-axis stabilized package (that includes TV camera, thermal sights, and a 5.56 mm automatic weapon) is

[4] It requires entrants to demonstrate the use of multi-vehicle robotic teams to execute an intelligence, surveillance and reconnaissance mission in a dynamic urban environment.

mounted on the roof of the Izci. It has various sensors, including stereo vision, color camera, drive cameras, GPS, and meteorological sensors. Table 32 shows other specifications of the Izci (IHS Jane's, 2011).

Height:	1.80 m		**Fording depth:**	0.28 m
Width:	1.40 m		**Max payload:**	200 kg
Length:	2.60 m		**Portable control station:**	
Weight:	400 kg		Length:	0.51 m
Max speed:	90 km/h		Width:	0.40 m
Endurance:	8 h		Depth:	0.19 m
Max gradient climb:	15°		**Weight:**	15 kg
Curb clearance:	0.28 m		**Line of sight control:**	4 km
Turning circle:	4.17 m		**Frequency:**	UHF

Table 32. Izci Characteristics (From IHS Jane's, 2011)

b. Gezgin

Figure 26. Gezgin (From IHS Jane's, 2011)

The Gezgin, meaning "Traveler," is a medium-tracked reconnaissance and armed UGV under development by ASELSAN. It uses the same control system as Izci, and there are plans for it to be guided by either fiber-optic cable or radio. It has a built-in collision avoidance system, a rear observation camera, a TV-camera sight, and 5.56 mm and 7.62 mm weapons. Its height, width, and length are 0.40 m, 0.50 m, and 0.90 m, respectively. The R&D phase is still ongoing (IHS Jane's, 2011).

c. T-Robot

Figure 27. T-Robot (From IHS Jane’s, 2011)

The T-Robot, developed by KOMPOZITEK, is a medium-armed, tracked or wheeled, reconnaissance, EOD- and IED-defeating UGV. It has six cameras and a manipulator. The base platform is fitted with front- and rear-driving cameras and lights and a pan/tilt/zoom surveillance camera, as well as weapons, a claw, and aiming cameras. Weapon options are EOD and IED defeating disruptors, M16 5.56 mm rifle, M240 7.62 mm machine gun, M82 Barrett .50 caliber semi-automatic rifle, and 40 mm grenade launcher. Other specifications of the T-Robot are shown in Table 33 (IHS Jane's, 2011).

Height:	0.80 m (approx.)		**Max gradient climb:**	40°
Width:	0.70 m		**Curb clearance:**	0.15 m
Length:	1.10 m		**Battery:**	Two 24 V gel batteries
Weight:	150 kg		**Line of sight control:**	250 m (radio frequencies), 100 m (cable)
Max speed:	4 km/h		**Manipulator arm:**	
Endurance:	2 h		**Max lift capacity:**	
Portable control station:			Extended:	15 kg
Length:	0.50 m		Unextended:	25 kg
Width:	0.30 m		**Max length:**	1.5 m
Depth:	0.20 m		**Max grip opening:**	25 cm

Table 33. T-Robot Specifications (From IHS Jane's, 2011)

d. NAT II

Figure 28. NAT II (From IHS Jane's, 2011)

The NAT II, developed by ELEKTROLAND, is a medium-tracked, explosives-defeating UGV. It is equipped with day/night cameras, a moveable robotic arm, pneumatic wheels, hydraulic and electric drive mechanism, and a rechargeable dry gel battery. The NAT II is capable of stair climbing with a max gradient of 40 degrees, rapid width reduction, two hours continuous operation, fording through up to 20 cm of water, and two-way communication for sound data and video. Its manipulator arm can carry 20 kg, touch objects 200 cm from the body of the vehicle, and carry a day/night camera. The R&D phase is still ongoing. Other specifications of the NAT II are shown in Table 34 (IHS Jane's, 2011).

Height:	0.40 m (approx., chassis)
Width:	0.50 m (approx.)
Length:	0.70 m (approx.)
Weight:	>100 kg
Max speed:	6 km/h
Endurance:	2 h
Max gradient climb:	40°
Gap clearance:	30 cm
Turning circle:	zero
Battery:	dry gel
Fording depth:	20 cm

NAT II portable control station	
Weight:	10 kg
Line of sight control:	500 m
Screen size:	15 cm

NAT II manipulator arm	
Lift capacity:	20 kg (extended, max)
Reach:	200 cm (max)
Weight:	13.5 kg (including 6 kg balance weight)
Base joint rotation:	360° continuous
Shoulder joint rotation:	150°
Elbow joint rotation:	120°
Wrist joint rotation:	150°
Gripper width:	23 cm
Gripper rotation:	360°, clockwise and anti-clockwise

Table 34. NAT II Specifications (From IHS Jane's, 2011)

IV. METHODOLOGY OF THE ANALYSIS

A. OVERVIEW

Having completed its establishment phase, the Turkish defense industry needs a competitive, well-structured acquisition system structured from the Turkish MND's standpoint. The acquisition practices in progress parallel the progress of the defense industry. Based on our open literature research, we could not find any source explaining an analysis method that determines the requirements of an MDS in the Turkish MND's acquisition system. Therefore, we chose another analysis method to get the answer to our primary research question: the "Analysis of Alternative" (AoA) model, which is an established method in the U.S. defense acquisition system.

An important element of the defense requirements and acquisition processes in the U.S. defense acquisition environment, AoA provides information to a decision making authority to debate and assess a potential program's operational capability and affordability. It also provides valuable information for the budgeting process (Office of Aerospace Studies, 2008).

According to the "AoA Handbook" (2008) of the U.S. Air Force:

> An AoA is an analytical comparison of the operational effectiveness, cost, and risks of proposed materiel solutions to gaps and shortfalls in operational capability. AoAs document the rationale for identifying and recommending a preferred solution or solutions to the identified shortfall(s). Threat changes, deficiencies, advances in technology or the obsolescence of existing systems can trigger an AoA. (p. 5)
>
> AoAs help justify the need for starting, stopping, or continuing an acquisition program. They are done because decision makers need reliable, objective assessments of the options for providing required capabilities. AoAs identify potentially viable solutions and provide comparative cost, effectiveness, and risk assessments of each solution to a baseline; this baseline is typically the current operating system. (p. 6)

In this chapter, we will introduce the AoA model, which we will use in the next chapter to make our analysis. The components of AoA are a concept of operations, required capabilities, capability gaps, threats, scenario, KPPs, MTs / MoEs / MoPs, effectiveness analysis, risk analysis, and alternative comparison matrix. We will not conduct a cost analysis within AoA because the required cost data is not available.

B. ANALYSIS OF ALTERNATIVES MODEL

1. Concept of Operations

Defining the concept of operations is the first step of AoA, and all of the other steps are structured according to this one. Military specialists generally describe operational concepts for three different periods: peacetime, contingency, and wartime (Defense Acquisition University [DAU], 2011). These operational concepts include the detailed alternatives of a specific operation for each period (Office of Aerospace Studies, 2008).

> Evaluating the effectiveness, cost and risks of an alternative requires a significant level of understanding of the operations of the alternative. For each alternative, an operations concept must describe the details of the employment of the alternative, as it will function within established military organizations. (Office of Aerospace Studies, 2008, p. 20)

The following list details many of the potentially appropriate issues an operations concept may discuss:

> - Deployment plans, including how the system will be deployed and its deployment schedule
> - When and how the system will be employed, including tactics
> - Logistics concepts for peacetime and wartime
> - Interoperability with other Air Force, sister service, and allied systems
> - Incorporation into existing organizational structures, including manpower impacts
> - The relationship of the concept of employment (CONEMP) to relevant Air Force (AF) or Joint Concept of Operations (CONOPS)
> - Peacetime and wartime operations concept (Office of Aerospace Studies, 2008, p. 20)

2. Required Capabilities / Capability Gaps

Capability is defined as "the ability to execute a specified course of action. It is defined by an operational user and expressed in broad operational terms in the format of an initial capabilities document" (ARCIC, 2010, p. C-4).

According to the ARCIC (2010), capability gaps are described as "those synergistic resources (DOTMLPF[5]) that are unavailable but potentially attainable to the operational user for effective task execution. These resources may come from the entire range of DOTMLPF solutions" (p. C-4).

3. Threats

The DAU (2009) defines a threat as "the sum of the potential strengths, capabilities, and strategic objectives of any adversary that can limit or negate U.S. mission accomplishment or reduce force, system, or equipment effectiveness" (p. B-185).

Common threat elements might include:

- The enemy order of battle
- Limitations on threat effectiveness, such as logistics, command and control, operational capabilities, strategy or tactics, and technology
- Countermeasures and changes in enemy strategy and tactics in response to the new system's capabilities (i.e., reactive threats)
- A range of threats to account for uncertainties in the estimates
- A target set representing a cross section of all possible targets
- Threat laydown showing potential threat systems and their location (Office of Aerospace Studies, 2008, p. 18)

4. Scenarios

After setting the threats, the different alternatives are considered. That study, in realistic operational settings, will provide reasonable comparisons of relative performances for different alternatives. The AoA does this by developing one or more

[5] DOTMLPF stands for Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities.

appropriate military scenarios. Scenarios define operational locations, the enemy order of battle, and the corresponding enemy strategy and tactics (“the threat”) (Office of Aerospace Studies, 2008).

5. Key Performance Parameters (KPPs)

KPPs are described in the DAU’s “Glossary of Defense Acquisition Acronyms & Terms” (2009) as:

> Those attributes or characteristics of a system that are considered critical or essential to the development of an effective military capability and that make a significant contribution to the characteristics of the future joint force. A KPP normally has a threshold representing the minimum acceptable value achievable at low-to-moderate risk, and an objective, representing the desired operational goal but at higher risk in cost, schedule, and performance. (p. B-100)

The AoA provides information for decision-making about the program. If the program is warranted, one of the main objectives of the AoA is to identify the KPPs (Analysis of Alternatives, 2005).

6. Mission Tasks (MTs) / Measure of Effectiveness (MoEs) / Measure of Performance (MoPs)

MTs are described as:

> Mission tasks are usually expressed in terms of general tasks to be performed to correct the gaps in needed capabilities (e.g., hold targets at risk, or communicate in a jamming environment). (DAU, 2011, p. 120)

> They are usually expressed in terms of general tasks to be performed or effects to be achieved (e.g., hold targets at risk, provide countermeasures against surface-to-air missiles, or communicate in a jamming environment). (Office of Aerospace Studies, 2008, p. 22)

The “AoA Handbook” of Office of Aerospace Studies (2008) describes MoEs as:

> MoEs are a qualitative or quantitative measure of a system‘s performance or characteristic that indicates the degree to which it performs the task or meets a requirement under specified conditions. They are a measure of operational success that must be closely related to the objective of the mission or operation being evaluated. There will be at least one MoE to

> support each MT. Each alternative is evaluated against each MoE, and the results are used for comparison among the alternatives. (p. 23)

MoPs are described as:

> MoPs are typically a quantitative measure of a system characteristic (e.g., range, velocity, mass, scan rate, weapon load-out, etc.) chosen to enable calculation of one or more MoEs. MoPs may apply universally to all alternatives or, unlike MoEs; they may be system specific in some instances. In order to determine how well an alternative performs, each MoP should have a threshold value. (Office of Aerospace Studies, 2008, p. 24)

7. Effectiveness Analysis

Effectiveness Analysis is described in the "AoA Handbook" of Office of Aerospace Studies (2008) as "the most complex element of the AoA and consumes a significant fraction of AoA resources. The goal of the effectiveness analysis is to determine the military worth of the alternatives in performing mission tasks (MTs)" (p. 21).

Effectiveness analysis is used to compare the alternatives dependent upon their military worth. It includes, and is affected by, MTs, MoEs, MoPs, alternatives, operations concept, threats, scenarios, study schedule, and available analysis resources. The effectiveness analysis methodology must be systematic and reasonable, and it should be straightforward enough that it does not contain any biases against any alternative (Office of Aerospace Studies, 2008).

Most AoAs consist of analyses at different levels of detail. In the overall analysis, the input of aggregate analyses utilizes the outputs of more specialized analyses. At each level, appropriate models (simulation or otherwise), other analytic techniques, and data should be identified to establish the effectiveness of the analysis methodology. This identification should be based on the MoEs that were previously selected. The models should be used for the computation of specific MoEs (DAU, 2011).

8. Risk Analysis

The "AoA Handbook" of Office of Aerospace Studies (2008) describes risk analysis as "the likelihood of an adverse event and the severity of the consequences should that event occur. The first step in risk analysis process is to determine what factors, under each risk category, are relevant to each alternative" (p. 39).

The following shows the potential factors of technological risks:

- Technology maturity
- Modularity
- Open architecture
- Extensibility (Office of Aerospace Studies, 2008, p. 39)

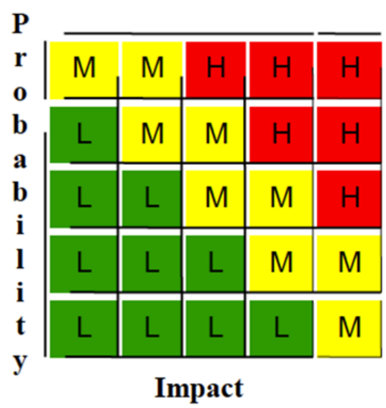

Figure 29. Notional Risk Assessment Matrix (From Office of Aerospace Studies, 2008)

9. Alternative Comparison Matrix

After all of the analyses have been presented, a summary lists the key points of each alternative side-by-side before presenting the conclusions and recommendations. This will ensure that the audience has a summary picture of the results in mind for the conclusions and recommendations part of the presentation (Office of Aerospace Studies, 2008).

V. ANALYSIS OF THE BEST AVAILABLE UGV

Based on Turkish efforts made in terms of UGVs, we will analyze in this chapter the Turkish MND's UGV requirements to find out the best available UGV on the market. First of all, we will examine the needs of the Turkish MND, employing the AoA model and producing the concept of operations, required capabilities, capability gaps and threats. We will also explore a scenario and examine the KPPs and MTs / MoEs / MoPs for a UGV that the Turkish MND needs. Secondly, we will analyze the selected UGV alternatives, performing an effectiveness analysis, a risk analysis, and generate an alternative comparison matrix.

A. THE REQUIREMENTS OF THE TURKISH MND FOR UGVS

1. Concept of Operations

The Turkish MND has difficulty protecting military convoys from terrorist attacks in the southeastern region of Turkey, where terrorist attacks on convoys produced casualties and damage. A UGV should be capable of detecting enemy forces in that region and neutralizing threats aimed at convoys. Therefore, the UGVs under study/consideration would be deployed in the southeastern part of Turkey.

The UGV must protect friendly forces, assist against terrorist attacks to the convoy, and conduct such missions as ambushes and security patrols. In security missions, the UGV might be used to explore places where units would be exposed to fire and to help prevent the enemy from taking action and observing units. In the event of an attack, it could help protect the units in the convoy by disrupting and causing harm to the enemy. Thus, a UGV would be beneficial for a better force protection posture of the Turkish MND (Computing Technologies, Inc. [CoTs], 2001).

The UGV would give early warning to friendly forces if it detects any enemy presence. The leader of the convoy and the Combat Operation Center (COC) would receive real-time data collected by the UGV, so the commander would be able to make early decisions for the safety of the convoy while staying away from enemy strengths and exploiting enemy weaknesses (CoTs, 2001).

In addition, the UGV would perform scouting, screening, and reconnaissance missions, assisting in the exploration of primary roads, as well as such adjacent terrain as defiles and lateral routes. It would reconnoiter risky areas and points of interest where enemy forces might be contacted, scout planned routes ahead of the operation, and observe critical locations in the southeastern part of Turkey. Working together with reconnaissance units and UAVs, the UGV would transmit data to the leaders of convoys and to the COC in deep reconnaissance or advance force operations. Mounted and dismounted reconnaissance units would benefit from the help of UGVs, as the success rate of reconnaissance would increase (CoTs, 2001).

The UGV should be able to both avoid detection by enemy forces with its high mobility and stealthy features – including a low visual, acoustic, and thermal signature – and be carried by a medium lift helicopter. The UGV must be compatible with Command, Control, Communications, Computers, and Intelligence (C4I) architecture and interoperable with current intelligence systems and UAVs (CoTs, 2001).

2. Required Capabilities

Able to perform RSTA missions with its beyond-obstacle detection and identification for navigating capabilities, the UGV would discover possible threats caused by the enemy. It should have the capability of operating under all weather conditions, day and night, in urban and rural terrain. It should also be capable of crossing ponds, lakes and other slow moving bodies of water and driving up to the speed of at least 100 km/h on roads and in open terrain (NRC, 2002).

There are other demands. The UGV must be capable of autonomously preceding or following a unit leader or moving on a flank as ordered, and doctrine (tactics, techniques, and procedures), local terrain, higher headquarters' guidance, and the leader's order would set the standoff distances between the UGV and the convoy leader. Capable of sensing the position of the leader and the other vehicles in the convoy and perceiving the terrain, the UGV should be easily able to implement orders from the leader with HRI capability in its missions. With a sophisticated sensor package for alerting the unit of potential threats, making eyes and ears of the leader, and the capability of 360-degree observation or still focus on a particular area, it would distinguish and communicate the presence of natural and manmade features, people, vehicles, obstacles and other objects. The UGV should be capable of transmitting all gathered information to both the leader and the COC (NRC, 2002).

UGV reliability must be high. Also, the unit should be able to self-diagnose, store maintenance problems for conducting corrective and preventive maintenance after the mission, and report critical problems to the leader and the COC immediately (NRC, 2002).

The functions and basic capabilities of UGVs needed by the Turkish MND, as specified in the NRC report (2002), are given in Table 35.

Function	Basic Capabilities
Mobility	• Operate day and night under all weather conditions • Crosses urban and rural terrain with same ability as section leader's manned vehicle • Swims water obstacles without additional preparation • Variable speeds depending on situation but up to 100 km/h on roads or in open terrain
Mission packages	• Local and global terrain, vegetation, obstacle sensing • Highly sophisticated sensors and range finders • Highly sophisticated RSTA package; Highly sophisticated Automated Target Recognition (ATR) that can discriminate among vehicles (combat and commercial) and humans (friend, foe, and noncombatant) • Stealth capabilities that make enemy detection of any UGV very difficult • Non-lethal self-protection package
Communications	• Secure communication package forms basis for "electronic tether" control/information sharing between the UGV and human section leader • Near real-time transfer of sensor and other information to section leader
Human control	• Human very easily directs the UGV to new locations and describes tasks to be performed by UGV while en route and upon arrival at new location • Human monitors sensor and other input from the UGV • Actively makes go or no-go decisions on all UGV recommended calls for direct or indirect fire
Automated UGV self-control and decision making	• Automatically moves in relation (precedes, follows, or on a flank) to manned vehicle as initially making directed; adjusts speed and movement direction based on terrain, vegetation, nearby vehicles, or other objects • Occupies and adjusts its precise location in stationary positions; ties in observations and fields of fire with adjacent manned or unmanned systems • Automatically calls for recommended direct or indirect fire missions when sensing an enemy • Senses when under attack from direct or indirect fire and takes appropriate action • Recognizes commands to change allegiance to a different human section leader, as necessary
Other	• High levels of maintenance reliability • Self-diagnosis and storing of anticipated noncritical maintenance problems; immediate reporting of critical maintenance issues to section leader
Human support	• No more than one assistant section leader and one maintenance technician both of whom ride in the manned section leader's vehicle

Table 35. Functions and Basic Capabilities of a UGV that Turkish MND Needs (From NRC, 2002)

3. Capability Gaps

a. The Turkish MND

In mountainous southeastern Turkey, the Turkish MND has a limited capability to detect terrorists and counterattack the enemy. The MND most often detects the enemy with UAVs and intelligence sources, but without such help it is hard to detect small groups of people in the mountainous terrain and harsh climatic conditions of that region. These drawbacks also make military convoys vulnerable to the terrorist attacks, attacks which have become inevitable, most of the time, due to capability gaps in this area.

In spite of the fact that Turkish Armed Forces have continued to conduct operations against terrorist groups in the southeastern part of Turkey, in August 2011, Turkey was hit with 23 terrorist attacks, second most in the world according to the Centre of Excellence-Defense Against Terrorism (COE-DAT) Agency's Monthly Terrorism Report (2011). Eight clashes resulted in 7 deaths and 18 injuries. Terrorist IED[6] attacks resulted in 14 dead and 46 wounded (Centre of Excellence-Defense Against Terrorism, 2011). The trend of terrorist and IED attacks, and the percentage of IED attacks is shown in Figure 30.

[6] a.k.a roadside bomb.

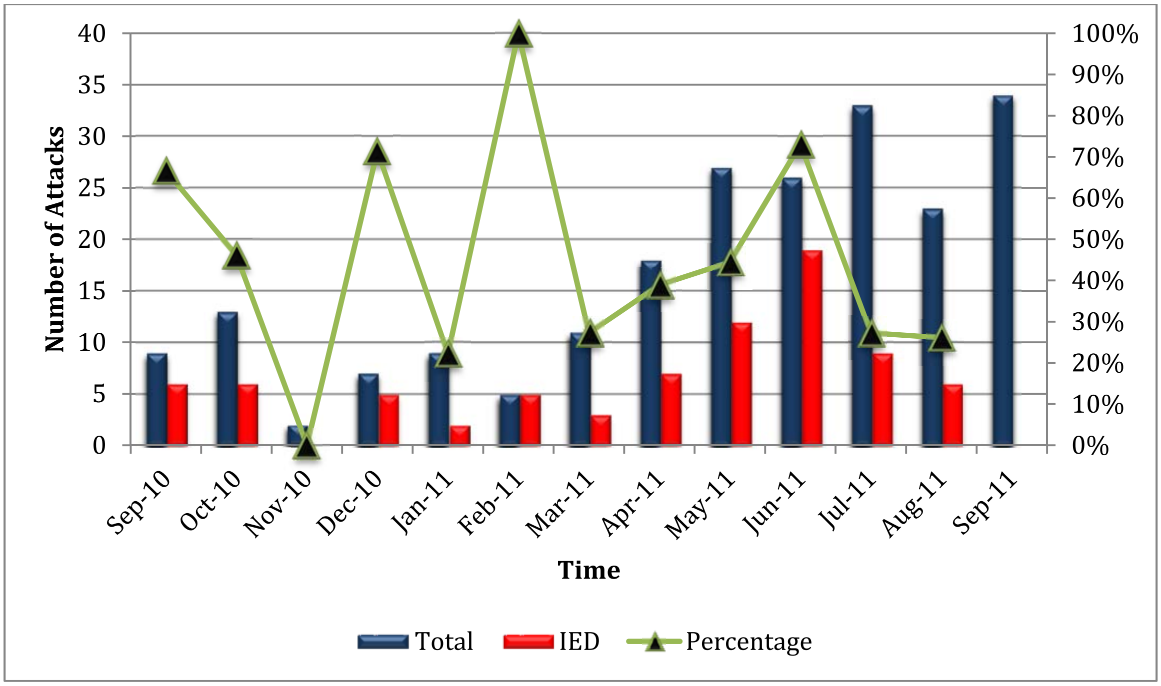

Figure 30. Trend of Terrorist Attacks

According to data pulled from Monthly Terrorism Reports, IED attacks constitute the most significant portion of the attacks. The main targets are logistic or personnel-transferring convoys. Attacks against these convoys are also conducted using mines. The incidents are devastating as the following accounts show.

> The soldiers, traveling in an M-113 armored personnel carrier scouting ahead of a military convoy, were killed near the town of Lice in the largely Kurdish southeastern province of Diyarbakir, on a stretch of highway linking the cities of Bingöl and Diyarbakir. Turkish Chief of Staff, General Ilker Başbuğ, told a press conference: "Our guess at the moment is that it was a homemade bomb of very powerful explosives. Most probably it was remote-controlled or detonated by cable." The attack, if confirmed, will be the deadliest by the PKK[7] this year. Shortly after the blast, the military launched ground and air operations against PKK separatists. (IHS Jane's, 2009)

> The air strikes were in retaliation for an ambush by the PKK on a military convoy on 17 August, which killed at least eight soldiers and a village guard, although some estimates put the number of those killed at as high

[7] According to the U.S. Department of State's "Country Reports on Terrorism" (2007), the PKK (Kurdistan Workers' Party) is listed as a terrorist organization internationally.

> as 12. At least 14 soldiers were injured in the attack, which involved four mine explosions along the road from Hakkari to Çukurca in Hakkari province in the far east of Turkey, bordering Iraq and Iran. (IHS Jane's, 2011)

The Turkish MND, having recognized this gap in protection, has used UAV procurement to improve the strength of Turkish Armed Forces in the operational area. Although UAVs provide vital benefits in the operational area, it is not enough for the full protection of the convoys. Therefore, in order to fill the gap, the Turkish MND needs a medium to large, platform-centric, autonomous ground vehicle that can perform deep RSTA missions in the southeastern part of Turkey to detect terrorists. This UGV must protect military convoys from ambushes, attacks, mines, IEDs, and direct/indirect fire incurred by asymmetric warfare.

b. UGVs

Current UMSs do not fulfill the interoperability requirements of the Turkish MND since they do not have common standards in terms of cooperation between ground and aerial vehicles and the controllers of the vehicles. The add-on C2, intelligence, and sensor payloads go beyond the size, weight, and power (SWaP) limitations for present platforms. They do not allow for teams of manned and unmanned systems to work well together. Multiple UMSs cannot coordinate and work together in operations because they do not have the required level of autonomy. Current UMSs cannot perform continuous operations since they do not possess the essential endurance (ARCIC, 2010).

UGVs are not able to support robust networks since they cannot fully transmit information and they cannot provide required capacity throughout the extended Operational Environment (OE). This affects the Common Operational Picture (COP) since it causes entire communications enterprise overload (ARCIC, 2010).

The UGVs do not have the ability to provide sufficient standoff distance from threats in the OE. They also cannot provide necessary mobility and extended weapons effects against enemy forces (ARCIC, 2010).

4. Threats

a. Threat to be Countered or Targeted

Terrorists in the southeastern part of Turkey conduct standoffs, hit-and-run attacks, and ambushes. In small groups, they carry out attacks against military convoys using mines, IEDs, and direct/indirect fire. Zehni (2008) describes the threats and points out the difficulties.

> The PKK's choice to use mountains at the common borders of Turkey and Iraq and Iran as a safe haven and as a front to conduct hit-and-run actions against Turkey was not an arbitrary choice. Throughout history these mountains have served as safe haven to bandits and smugglers, away from the reach of the central government's authority. Their rugged character hinders transportation and communications networks, and the small villages are far away from each other. The PKK chose these mountains to exploit the natural structure of this region as a safe haven, as a liberated area to prove that it is in charge in the region. Especially under these conditions, "the security of the people must be assured as a basic need, along with food, water, shelter, health care and a means of living." (p. 23)

b. Threats to UGVs

UGVs face physical destruction and neutralization threats from enemy forces in the form of sniper attacks, mines, indirect fire (rockets, mortars and artillery), and IEDs (ARCIC, 2010; CoTs, 2001). UGV sensors can also be targeted by direct-fire threats (CoTs, 2001).

Enemy tactics such as camouflage, concealment, deception and electronic warfare can be used to neutralize or degrade the capabilities of the UGV. Enemy electronic warfare systems might detect the UGV due to its signature. Enemy forces can affect UGV data communication links through jamming, disruption, and/or exploitation (CoTs, 2001).

5. Scenario

In this scenario, Red forces are comprised of a squad including small arms and several machine-gun teams on the flanks. They are in stationary defensive positions.

They hide in defilade where they have good lines of fire. They have buried a mine in the road and expect the Blue forces, but they do not have any information in advance (Army Science Board, 2001).

The Blue force is ambushed. The Blue force has a convoy of five trucks as well as an escort unit of an armored personnel carrier in a column formation. A medium to large platform-centric autonomous ground vehicle precedes the convoy. The armored personnel carrier travels ahead of the trucks. The convoy is moving through rolling hill terrain and a partially-developed road network. The area is mountainous and the road is narrow. The Red force sets up an ambush to disrupt the convoy (Starr, Johnson, & Dugone, 2004).

The UGV detects the mine and identifies the Red force. It transmits the information to the leader of the convoy and the COC. Exposed to machine-gun fire, the UGV senses the attack and gives the first response to the enemy with its non-lethal self-protection package. The UGV receives orders from the leader that it should find a position that allows for suppressive fire from the armored personnel carrier, neutralize the mine, and find a position that allows the Blue trucks to move after neutralization. The Blue escort looks for a covered position between the Red forces and the convoy, and provides the maximum amount of fire against the Red Forces. The UGV neutralizes the mine and finds a covered position while the Blue trucks continue to drive at the highest possible rate of speed. After the Blue trucks leave the kill zone, the UGV follows. Once the other forces leave, the Blue escort continues suppressive force, breaks contact, and leaves the kill zone (Hakola, 2004). The UGV transmits the information to the COC, if directed. Figure 31 depicts the convoy action against the ambush.

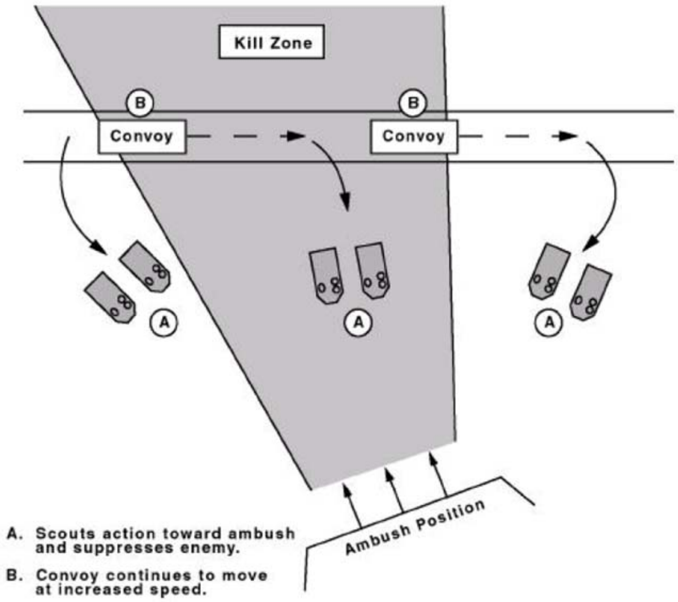

Figure 31. Convoy Escort Actions against Ambush (From U.S. Marine Corps, 2001)

5. KPPs

KPPs are generated based on the needs of the Turkish MND. They are determined as a result of analyzing the concept of operations, required capabilities, capability gaps, threats and scenario. They are critical capabilities that the Turkish MND needs to protect military convoys from terrorist attacks in the southeastern region of Turkey. KPPs for a medium to large platform-centric autonomous ground vehicle are given in Table 36.

KPPs	Criteria
Endurance	24 hrs.
System Range	300 km
Max Speed	100 km/h
Payload fraction	>40%
Reliability	.95 of failure free system over specified period of time

Table 36. KPPs for a Medium to Large Platform-Centric Autonomous Ground Vehicle that Turkish MND Needs

6. MTs / MoEs / MoPs

The MTs, MoEs, and MoPs are developed according to the needs of the Turkish MND for a medium to large platform-centric autonomous ground vehicle. They are also determined as a result of analyzing the concept of operations, required capabilities, capability gaps, threats and scenario. They are presented in Table 37.

MTs	MoEs	MoPs	Criteria
1. Mission Length	Endurance	Average mission hours	>24 hrs.
2. System Range	Range	Average range of system	>300 km
3. Mobility	Max Speed	Average Max Speed	>100 km/h
	Cross-country	Average Cross-country Speed	Average sustained speed of 60 km/h
	Fording Capability	Average Water Depth	>0.8 m
4. Mission Packages	Target identification	% of correct target identification	>95% of correct target identification
	Payload Capacity	% of payload fraction	>40% payload fraction
5. Communication	Communication Range	Average signal range	>10 km
	Communication Failure	% of time lost communications	<5% of time lost communications
	Communications Network	Average max number of systems in the network	>2 systems including the COC and the leader of the convoy
6. Human Control	Directing the UGV	% of time consistent implementing orders from leader	%99 of time consistent implementing orders from leader
7. Automated UGV Self-control and Decision making	Autonomous Obstacle Avoidance on Commanded Roads	% of detected obstacle	>99% of percent of detected obstacle
	Autonomous Navigation	% of time correctly following or preceding the vehicle	>99% of time correctly following or preceding the vehicle
	Exposure to threat	% of detecting direct or indirect fire	>%95 of detecting direct or indirect fire
	Detect Mines and IEDs	% of detecting mines and IEDs	>95% of detecting mines and IEDs
8. Other	Reliability	Probability of failure free system over specified period of time	>.95

Table 37. MTs, MoEs, and MoPs for a Medium to Large Platform-Centric Autonomous Ground Vehicle that Meets the Needs of the Turkish MND

B. ANALYSIS OF ALTERNATIVES

In this section, we will perform effectiveness and risk analyses and generate an alternative comparison matrix. The AoA method showed that the current systems available globally do not fully satisfy the MoEs and MoPs developed for the requirements of the Turkish MND because the technological advancements of supporting technologies do not completely support the needs outlined in Section A of this chapter.

Viable alternatives selected by the analyses are the Izci (Turkey), MDARS (USA), the GRUNT (Canada) and the Guardium (Israel). These UGVs have real-world applications, and they have been chosen since their capabilities are similar to the needs of the Turkish MND. Among the UGV alternatives, only the Izci has completed its development, although it has not yet been fielded. The other alternatives have been fielded. The Izci is selected as a baseline, since it is a product of the Turkish defense industry.

1. Effectiveness Analysis

Effectiveness analysis is performed based on the scores of each MoE for each viable alternative. Also, the overall score is determined for each UGV alternative.

First, the assessment of the relative dependence of relevant technology areas for the platform-centric autonomous ground vehicle is taken from the NRC (2002) report to weight the MoEs. Then, scores for each alternative UGV are assigned. The overall score for each alternative is then determined by weighting and summing the scores for each MoE:

Overall Score = $\sum W_i * S_i$

Where W_i is the weight of the i th MoE and S_i is the score of the i th MoE.

Table 38 summarizes the NRC report's (2002) assessment of the relative dependence of relevant technology areas.

Technology Area	Need/Relevance
Perception	
For A-to-B mobility	5
For situation awareness	5
Navigation	5
Planning	
For path	5
For mission	4
Behaviors and skills	
Tactical skills	4
Cooperative robots	5
Learning/adaptation	3
Human–robot interaction	4
Mobility	5
Communications	3
Power/energy	5
Health maintenance	5
Key to Ratings 0 = no need, 1 = low need, 2 = below average need 3 = average need, 4 = above average need, 5 = high need	

Table 38. Relative Dependence of Technology Areas (From NRC, 2002)

Table 39 shows the scoring values and weights assigned to each MoE. Weights assigned are based on the relative dependence of technology areas. The maximum overall score is 135.

				Scoring Value				
MTs / MOEs	Technology Area	Weight	Notes	1	2	3	4	5
1. Mission Length	Power/Energy	5						
1.1. Endurance			Hours	x<12	12≤x<24	24≤x<48	48≤x<72	72≤x<96
2.Automated UGV Self-control and Decision Making	Navigation	5						
2.1. Autonomous Navigation				Preprogrammed waypoint		Waypoint plus obstacle avoidance		Able to precede or follow the leader
3. Communications	Communications	3						
3.1. Communications Network				Wireless comms		Redundant comms - (two or more systems)		Comms network and HRI (able to respond words, whistle, and arm signals, etc.)
4. Mobility	Mobility	5						
4.1. Max Speed			km/h	x<8	8≤x<15	15≤x< 40	40≤x< 80	80≤x
5. Mission Packages	Perception	5						
5.1. Payload Capacity			kg	x<75	75≤x<150	150≤x<250	250≤x<500	500≤x

Table 39. Scoring Values and Weights for Each MoE[8] (From Holste et al., 2009)

[8] "Payload Capacity" MoE doesn't fully satisfy the "Perception" technology area. But, it is assumed that the "Perception" is the closest technology area to this MoE among the other technology areas.

MoEs	**Izci (Baseline)**	Score	Weight	Total Score	**MDARS**	Score	Weight	Total Score
1.1. Endurance	8 h	1	5	5	16 h	2	5	10
2.1. Autonomous Navigation	Waypoint plus obstacle avoidance	3	5	15	Waypoint plus obstacle avoidance	3	5	15
3.1. Comms Network	Wireless comms	1	3	3	Redundant comms – (two or more systems)	3	3	9
4.1. Max Speed	90 km/h	5	5	25	32 km/h	2	5	10
5.1. Payload Capacity	200 kg	3	5	15	139 kg	2	5	10
			Overall Score	**63**			Overall Score	**54**

Table 40. Izci and MDARS Scores and Overall Scores

MoEs	**GRUNT**	Score	Weight	Total Score	**Guardium**	Score	Weight	Total Score
1.1. Endurance	Varies depending on mission	2 (Assumed to be between 12 and 24)	5	10	24 hours and up to days of continuous operation	3	5	15
2.1. Autonomous Navigation	Waypoint plus obstacle avoidance	3	5	15	Waypoint plus obstacle avoidance	3	5	15
3.1. Comms Network	Redundant comms – (two or more systems)	3	3	9	Redundant comms – (two or more systems)	3	3	9
4.1. Max Speed	30 km/h	2	5	10	50 km/h (in semi-autonomou s mode)	4	5	20
5.1. Payload Capacity	771 kg	5	5	25	300 kg	4	5	20
			Overall Score	**69**			Overall Score	**79**

Table 41. GRUNT and Guardium Scores and Overall Scores

Based on the scores, effectiveness analysis is conducted for each viable alternative. Results are shown in Table 42.

Alternatives	MTs					Overall Scores
	1. Mission Length	2. Automated UGV Self-Control and Decision Making	3. Communications	4. Mobility	5. Mission Packages	
	MOEs					
	1.1. Endurance	2.1. Autonomous Navigation	3.1. Comms Network	4.1. Max Speed	5.1. Payload Capacity	
Izci (Baseline)						63
MDARS						48
GRUNT						69
Guardium						79
Criteria: (x = Scores) Red: x≤2, Yellow: 2<x≤4, Green: x=5						

Table 42. Effectiveness Analysis Results

2. Risk Analysis

First of all, criteria are developed to determine the impact and probability of the viable alternatives for conducting risk analysis. Table 43 explains the impact criteria and Table 44 illustrates the probability criteria.

Impact	Justification
1	Minimal impact to Turkish MND in terms of satisfying the needs for the UGVs
2	Low impact to Turkish MND
3	Moderate impact to Turkish MND
4	Moderate to High impact to Turkish MND
5	High impact that doesn’t satisfy the needs of the Turkish MND.

Table 43. Impact Criteria

Probability	Probability of Occurrence	Justification
1	0%<X<10%	Low probability due to proven technology
2	10%<X<40%	Limited probability
3	40%<X<60%	Moderate probability
4	60%<X<90%	Fair probability
5	>90%	High probability due to unproven technology

Table 44. Probability Criteria

After the criteria are defined, each alternative is judged subjectively (relative to the criteria) to determine the risk. Table 45 summarizes the risk analysis of each viable alternative. The "Rationale" column presents a short explanation of the decisions used for the numbers assigned to the impact and probability for each UGV alternative. The product of the impact and probability scores is, basically, the number for risk.

No	Alternative	Rationale	Impact	Probability	Risk
1	Izci (Baseline)	According to IHS Jane's (2011), development of the Izci is completed. But, it has not been fielded yet. There are uncertainties about the reliability of the system, and technologies related to the UGV have not been proven in the field. The Izci is the closest system that fulfills the needs of the Turkish MND explained in section A of this chapter. It is capable of conducting missions including asymmetric warfare, border surveillance, homeland security, logistics, perimeter patrol of high-value installations, observation, and reconnaissance.	2	4	8
2	MDARS	According to IHS Jane's (2011), the MDARS is in service with the U.S. Department of Energy and the U.S. Army. It has completed 8,000 hours of operation and more than 45,600 km of security patrols since October 2004 at Hawthorne Army Depot (HWAD) in Nevada. Also, the first of three MDARS was delivered to the Nevada National Security Site (NNSS) in October 2010, according to the National Nuclear Security Administration (NNSA). Therefore, the technologies are assumed to be proven in the field. In terms of the requirements, the roles for the vehicle include providing security and performing a patrol role for DoD warehouses, airfields, ammunition supply depots, and port facilities. Therefore, it is the furthest system with respect to satisfying the needs of the Turkish MND.	5	2	10
3	GRUNT	IHS Jane's (2011) shows that development of the GRUNT is completed and it is in service. A Mobile Autonomous Guard System, including two GRUNTs (that are based on the Argo All-Terrain-Vehicle), a base station command and control system, and a complete software development environment, were delivered to South Korea in 2005 by the developer. Therefore, the technologies are assumed to be proven in the field. It can perform missions including perimeter security and surveillance of critical infrastructure. Therefore, it does not fully satisfy the needs of the Turkish MND.	4	2	8
4	Guardium	IHS Jane's (2011) shows this UGV is in service with the IDF. It was tested by Israel's Airport Authority in 2008, and the IDF has been deploying Guardiums along the Gaza border since 2011. Therefore, it is assumed that it has technologically proven itself in the field. The Guardium can perform missions including patrol, route proving and convoy security, reconnaissance and surveillance, and combat logistic support. So, its roles are close to the needs of the Turkish MND.	2	2	4

Table 45. Risk Analysis

Finally, the risk analysis is mapped onto a risk reporting matrix. The matrix graphically shows where each viable alternative fell in the "risk space." Figure 32 presents this mapping. The level of risk for each alternative is reported as low (green), moderate (yellow), or high (red).

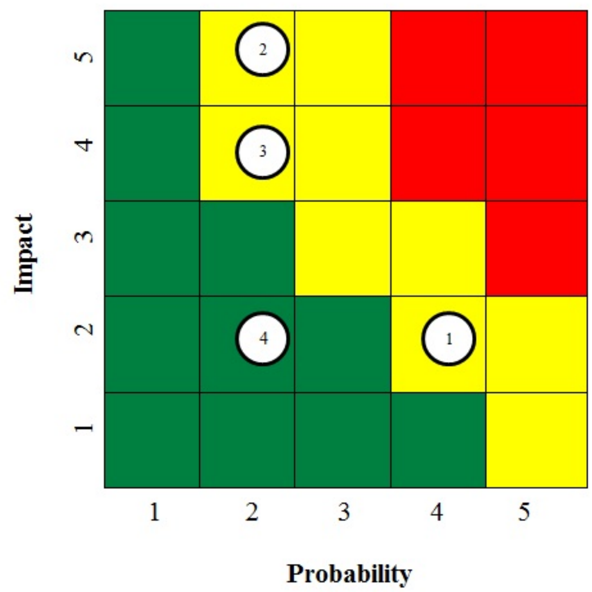

Figure 32. Risk Reporting Matrix

3. Alternative Comparison Matrix

The alternative comparison matrix is generated based on the results of the effectiveness analysis and the risk analysis. Critical and non-critical MoEs are determined according to the weights of each MoE. "Communications Network" is the only MoE with a weight of less than five, so it is regarded as non-critical. The resultant matrix is shown in Table 46.

	Critical				Non-Critical		
	MT 1. Mission Length	MT 2. Automated UGV Self-Control and Decision Making	MT 4. Mobility	MT 5. Mission Packages	MT 3. Communications		
	MOE 1.1. Endurance	MOE 2.1. Autonomous Navigation	MOE 4.1. Max Speed	MOE 5.1. Payload Capacity	MOE 3.1. Comms Network	Risk	Overall Scores
Izci (Baseline)	R	Y	G	Y	R	Y	63
MDARS	R	Y	R	R	Y	Y	54
GRUNT	R	Y	R	G	Y	Y	69
Guardium	Y	Y	Y	Y	Y	G	79

Table 46. Alternative Comparison Matrix

The resultant alternative comparison matrix is constructed by applying the AoA method (without cost analysis). Among the viable alternatives, the Guardium is selected as the best available alternative in terms of satisfying the requirements of the Turkish MND. The ranking of other alternatives is from preferred choice to least preferred: the GRUNT, Izci, and MDARS. However, of consideration is that the Izci has not yet been fielded, so has not proven itself technologically in the field.

The Guardium can only partially fill the capability gaps of the Turkish MND because its state-of-the-art technology does not allow a fully autonomous system, able to detect terrorists and take necessary actions in an operational environment. As technology advances, there will be much better systems to fill the capability gaps.

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VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This MBA Project focused on finding the best available UGV on the current market with respect to the requirements of the Turkish MND. UGVs can perform dull, repetitive, and dangerous missions, and they are also capable of saving the lives of military personnel in an operational environment. Today, countries have started to invest in UGVs. In Turkey, there is a growing interest in UGVs and supporting technologies in the Turkish MND and defense industry.

In this study, first of all, we introduced an overview of UGVs and then explored the concept of unmanned vehicles and UGVs, as well as their types and supporting technology areas. We conducted market research and gave examples of UGVs from the current market of selected countries. After we explored UGVs, we recognized that the most important challenge with the supporting technologies for unmanned ground systems is autonomy. A fully autonomous system has not been developed yet, and it is not likely one will be developed in the short term, as explained in Chapter II.

Secondly, we explained the current UGV efforts within the Turkish MND. We provided a background and described the technology management strategy of the Turkish MND, introducing current UGV efforts in the Turkish defense industry. We showed that there is a growing interest in UGVs in Turkey and that Turkish defense companies have started to invest in the infrastructure of unmanned systems to improve capabilities. A few UGVs, such as the Izci, Gezgin, T-Robot, and NAT-II, have been developed or in the process of being developed. Despite these efforts in the industry, no signed contract exists, nor are there other UGV activities, in the Turkish MND.

Thirdly, we introduced the AoA methodology model which is used in Chapter V. The AoA model provided the framework for determining the capability gaps and the requirements of the Turkish MND and the best available UGV in the current market.

Finally, we performed an analysis to determine the best available alternative in the current UGV market with respect to the requirements of the Turkish MND. We presented the concepts of operations, needed capabilities, capability gaps, and threats and then developed a scenario and generated KPPs and MTs / MoEs / MoPs. These steps provided the data we needed to determine the needs of the Turkish MND. We concluded that the Turkish MND needs a medium to large platform-centric autonomous ground vehicle that would protect convoys from ambushes, IEDs, mines, and direct/indirect fire. The Turkish MND has limited capability to detect terrorists in the mountainous areas in the southeastern region of Turkey. Terrorists there conduct standoff and hit-and-run attacks, inflicting losses and causing damage to military convoys. In order to fill the gap, the Turkish MND must employ a medium to large platform-centric autonomous ground vehicle that would protect convoys from these threats.

Last but not least, we performed both effectiveness and a risk analyses, and generated an alternative comparison matrix. The viable alternatives selected for the analysis part of the AoA method were the Izci (Turkey), MDARS (USA), GRUNT (Canada), and Guardium (Israel). These vehicles were chosen due to their close relationship with the needs of the Turkish MND and because they have real-world applications.

Once the effectiveness and risk analyses results were determined, an alternative comparison matrix was generated to compare the viable alternatives. The ranking of the alternatives are as follows, from most suitable to least suitable, according to the results of the matrix: the Guardium, GRUNT, Izci, and MDARS. It should be considered that the Izci has neither fielded nor technologically proven in the field (unlike the other UGVs). The results showed that the best available alternative in the current UGV market with respect to the requirements of the Turkish MND is the Guardium. This unmanned system can partially fill the capability gaps of the Turkish MND which result from current technological limitations.

B. RECOMMENDATIONS FOR FURTHER RESEARCH

First, we recommend extending the market research. In this study, we conducted market research for selected countries—mostly developed countries. However, the defense industries of developing countries might provide unique, and possibly better, products.

In this study, we realized that the defense acquisition system of the Turkish MND is still in progress, so we introduced the U.S. AoA methodology to perform our analysis. We recommend that a study be conducted to find the gaps and areas needing improvement of the Turkish defense acquisition system by comparing it with the defense acquisition systems of other countries.

We performed an effectiveness analysis and a risk analysis in this study. For an effectiveness analysis, various tools can be used. The use of modeling and simulation (M&S) tools can be especially beneficial. Moreover, a sensitivity analysis can extend the robustness of the effectiveness analysis. In terms of risk analysis, we only focused on technological risks. This study could be further extended to consider programmatic and operational risks.

Another important step in the AoA decision process is cost analysis. Cost analysis results are combined with the effectiveness and risk analysis results in the alternative comparison matrix. This study did not explore the total life cycle (LCC) cost of each alternative because of time and data constraints. Therefore, we recommend that this study be extended with an LCC analysis for each alternative so that more accurate results for comparison can be achieved.

In this study, we realized there is no UGV on the current market that fully satisfies the requirements of the Turkish MND. At the moment, the best UGV (which partly fulfills the requirements of the Turkish MND) is the Guardium. This system should be procured to immediately close the capability gaps and should then be improved incrementally. Further research could explore the incremental development areas of the procured best alternative.

This study might also be applied to other research areas. These include:

- Application of this study to UUVs, USVs and UGSs for the Turkish MND
- Exploration of concepts in this study in terms of country interests, political issues, security objectives and improvement of the Turkish Defense Industry

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