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Human-Autonomy Teaming Essential Research Program Project 2: Transparent Multimodal Crew Interface Designs
Technical Note 1: General Overview

by Brandon S Perelman, Shan Lakhmani, and Julia L Wright

NOTICES

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Technical Note 1: General Overview

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14. ABSTRACT

This technical note, the first in its series, describes a general overview of the US Army Combat Capabilities Development Command Army Research Laboratory’s (ARL’s) second project in the Human-Autonomy Teaming Essential Research Program, transparent multimodal crew interface designs, in support of the US Army modernization priority Next Generation Combat Vehicle (NGCV). The goal of this project was to improve crew members’ understanding of autonomous systems’ actions, intentions, goals, and general reasoning by at least 25%. To achieve this goal, a team of ARL scientists and contractor engineers implemented iterative improvements to the NGCV Warfighter machine interface aimed at addressing multiple stages of the mission, from planning to execution. Interface improvements included a multimodal (tactile and auditory) cueing system designed to improve crew members’ local situation awareness while commanding simulated autonomous robotic combat vehicles, a display for evaluating tradeoffs in the Multi Domain Operations battle space, and improvements to existing route planning functionality. These interface improvements were implemented and tested in ARL’s Information for Mixed Squads Laboratory, which permits the simulation of up to platoon-level operations. This note describes a general overview of the research project, including scientific basis, facilities/apparatus, goals, and metrics.

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1. Introduction

The Human-Autonomy Teaming (HAT) Essential Research Program (ERP) roadmap defines several focused research lines (i.e., projects) to be completed in the upcoming years. Within this research plan are also two decision points, where the overall program will be reviewed and revised as needed. Decision Point (DP) 1 occurred at the end of FY19, and its goal was to demonstrate a 25% increase in a crew's comprehension of unmanned vehicle actions, intentions, goals, and general reasoning. HAT ERP Project 2's objective was the development of multimodal, transparent crew interface designs to meet DP 1's goal and satisfy Project 2's objectives.

These concepts are implemented as modifications to the Warfighter Machine Interface (WMI) software intended for use in one of the US Army's Modernization Priorities, the Next Generation Combat Vehicle (NGCV). These concepts will be incorporated into the WMI, and tested against the baseline WMI system, by means of simulations taking place in the Information for Mixed Squads (INFORMS) laboratory. These transparency concepts are intended to provide the NGCV crew with improved understanding of autonomous systems during the planning and execution phases of the mission; other HAT ERP projects will address these phases as well as the after-action review that follows mission execution. This technical note describes background on Project 2's collaborative effort among the US Army Combat Capabilities Development Command (CCDC) Army Research Laboratory (ARL) scientists and Direct Contract Services Inc. (DCS) engineers to integrate novel concepts into the WMI for near-term future transition into NGCV.

1.1 Operational Definitions

For HAT ERP Project 2, we operationalize the language of DP1 in the following way. First, we define *crew* as the smallest unit size that will permit us to test both system- and unit-level interactions using the WMI. In order to support dynamic task orchestration across crew members and the integration of technologies designed to improve multivehicle mobility, we define *crew* in terms of a *decisive lethality section* consisting of one Manned Combat Vehicle (MCV), and two Robotic Combat Vehicles (RCVs), with the option to scale up to platoon-level operations (i.e., two sections). Furthermore, we define the DP1 goal constructs, *actions*, *intentions*, *goals*, and *general reasoning* in Table 1. For the purpose of this project, we specifically focus on testing these goal constructs as they pertain to operations tempo (optempo) mobility in complex unstructured environments, where the vehicle's autonomy does not have a priori information about the presence of road networks but has limited information about obstacles in the environment.

Table 1 Operational definitions for DP1 goal constructs

Construct	Definition
Actions	Activities that the vehicle is currently executing, either under the control of autonomy or a human, its current status, and its location in the environment.
Intentions	The sequence of Actions required for a vehicle to achieve its Goals.
Goals	The state (at a given mission phase) that the crew, either through autonomy or human control, aims to achieve.
General reasoning	The underlying algorithms, heuristics, a priori information, and mechanisms that the RCV is using to achieve its Goals, as well as the functional limits of these.

1.2 INFORMS

INFORMS houses the Manned-Unmanned Teaming Experimentation Laboratory, Simulation in the Loop (MEL-SIL), which consists of the WMI software running on 14 mockup NGCV crew stations. The MEL-SIL laboratory is designed to permit the simulation of one full NGCV decisive lethality platoon, composed of two sections, each consisting of one MCV and two RCVs; see Fig. 1.

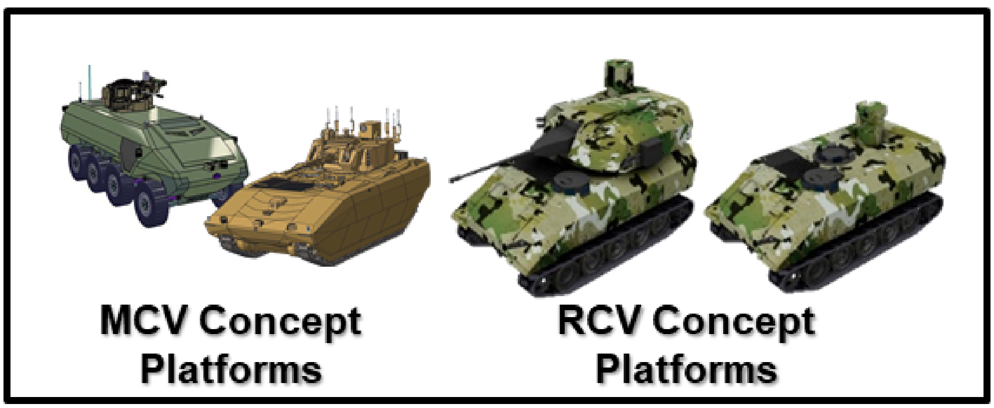

Fig. 1 NGCV MCV and RCV concept platform illustrations. (Source: Next Generation Combat Vehicle Cross Functional Team, 2018)

The 14 crew stations are split between two framed MCV mockups, each containing 7 crew stations and representing an individual decisive lethality section (Fig. 2). Our goal is not to design the physical NGCV platform interior, crew stations, or hardware requirements, nor is the MCV layout (shown in Fig. 2) intended to replicate a real-world vehicle. Instead, the configuration is intended to allow testing the effects of transparency concepts, intelligent technologies, novel teaming and communications dynamics, and training interventions on crew performance in a simulated environment.

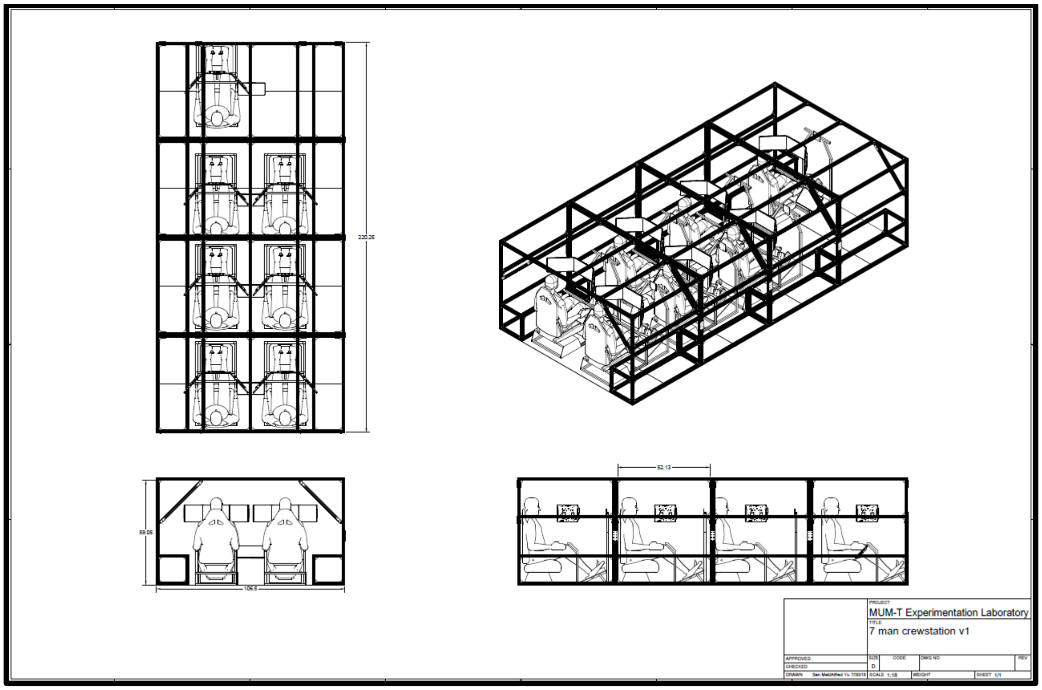

Fig. 2 MCV layout in the INFORMS lab MEL-SIL. Each row contains a dyad, primarily tasked with controlling (from back to front) each of the two RCVs, and the MCV itself. The front-most crew station seats a section-level commander.

Each crew station is equipped with three touchscreen displays, a steering yoke with integrated buttons, pedals, and other human interface devices such as a keyboard and wired mouse (Fig. 3). Furthermore, each crew station is equipped with a wired headset and microphone that permits the crew members to communicate over a TeamSpeak (TeamSpeak Systems, Inc., 2019) network hosted on an adjacent server.

Fig. 3 Crew station layout in the INFORMS lab MEL-SIL

The MEL-SIL crew stations are intended to mimic the functionality of real-world NGCV crew stations, using commercial off-the-shelf hardware, in order to support the rapid ideation, integration, and testing of HAT project software. Therefore, the MEL-SIL uses the same WMI and underlying software (i.e., the Robotic Technology Kernel; RTK) as the actual NGCV systems currently being tested by the CCDC Ground Vehicles System Center (GVSC). However, instead of interacting with the real world, all vehicle sensors and hardware are simulated using Autonomous Navigation Virtual Environment Laboratory (ANVEL) software (Quantum Signal 2019). The use of the actual WMI system and underlying software in a simulation environment allows us to test user-system interactions, teaming and communications dynamics, and failure modes, and create solutions to improve crew situation awareness, human-agent teaming, and ultimately performance.

1.3 General WMI Description

The WMI is an interface currently under development by CCDC GVSC and DCS Inc. for controlling both the manned (MCV) and unmanned (RCV) NGCVs. The WMI provides crew members with the ability to operate all of the vehicles' mobility and gunnery functions, maintain situation awareness during closed-hatch or unmanned vehicle operation, and communicate with other assets in the environment. Additional functionality allows crew members to create and update mission plans as well as establish and maintain common operating picture.

Crew members interact with the WMI primarily by means of touch screen and interface devices described in Section 1.2. The WMI is modular; a status bar at the bottom of the screen provides high-level information, and additional windows can be dragged and dropped onto the main screen to create portals of varying size. These portals facilitate vehicle functions, such as mobility and gunnery, as well as Command, Control, Communications, Computers, Combat Systems, Intelligence, Surveillance, and Reconnaissance (i.e., C5ISR) with other assets by means of maps, asset lists, threat lists, and reports. Units in the field are marked using MIL-STD-2525D (2014) battle space objects, or BSOs, and users can place these manually to develop a common operating picture. Depending upon changing mission needs, the WMI portals can be dynamically reconfigured as necessary. Importantly, a single crew station has the ability to log in to any vehicle in the platoon; as such, the ratio of crew members and the command structure are both malleable.

1.4 The Simulated Environment

The environment (Fig. 4) has been specifically engineered to represent several different types of terrain, allowing us to test the WMI under varying conditions of environmental complexity, including rural flat terrain, rural hilly terrain, suburban terrain composed of small- to medium-sized heterogeneous structures, and complex urban terrain containing a mixture of dense and relatively open areas (e.g., a park). Furthermore, the overhead mapping software for mission planning is not derived directly from the environment in real-time, but rather generated from a map ahead of time, representing pre-operational reconnaissance by intelligence, surveillance, and reconnaissance assets. This permits introducing complexity through the inclusion of agents (i.e., humans and animals), as well as environmental obstacles (e.g., vehicles, man-made obstacles, craters, rubble, debris) that may not be known to crew members during the planning phase. The terrain types in the simulated environment represent the type of complex variety expected in future operational environments, and include surfaces of varying mobility challenge for vehicles, such as unimproved mud roads, deep snow, grass, and pavement. Varying levels of environmental complexity and uncertainty are required to test how user-system interactions, user-system teaming, and communications dynamics interact with the types of complex, dynamic terrain features expected on the Army’s future battlefields.

Fig. 4 ANVEL simulated environment used for HAT Project 2 testing in the MEL-SIL. The top panel shows an aerial shot of the environment, which contains a mixture of rural, suburban, and complex urban terrain. Specific features include a factory, two parks, and a marketplace. The bottom panels show two types of human models included in the environment: (left) militia and (right) regular military forces.

In addition to environmental scenery objects, the environment contains scenario elements to be used as targets during experimentation. Figure 4 (bottom panels) shows two broad classes of humans in the environment (militia and regular military). Human models are available with a relatively wide variety of armament, including rifles and antitank weapons, which pose varying degrees of threat to friendly forces.

1.5 Transparent Multimodal Crew Interfaces Development Plan

HAT ERP Project 2 is intended to achieve the DP1 goals of improving the crew's understanding of the unmanned vehicle's actions, intentions, goals, and general reasoning. Project 2 consists of four separate iterations (Table 2), each addressing a different transparency concept, and comprises four phases.

- Phase 1: a rapid ideation phase among ARL scientists.
- Phase 2: a collaborative coding sprint requiring ARL scientists to work alongside DCS engineers.
- Phase 3: rapid iteration phase during which the integrated transparency concepts are internally tested and modified.

- Phase 4: an experimental testing phase in which crew performance using the newly integrated concepts is compared against performance using the baseline WMI.

The transparency concepts address potential HAT-related issues specifically associated with humans understanding intelligent agents, anticipated during high-optempo missions in complex, unstructured environments. Each iteration is designed to address a separate capability gap toward enabling optempo mobility in complex environments.

Table 2 Transparency concepts introduced during each iteration

Iteration	Baseline capability	Capability gap	Project 2 concept
1	On-road waypoint navigation + teleoperation	Teleoperation requirement off-road potentially increases crew workload to unacceptable level.	Transparent Route Planner (TRP) + comparator display
2	Situation awareness (SA) supported through radio communication	Allocentric to egocentric translation issues exacerbated by remotely operating vehicles. Verbal comms clog nets.	Multimodal-cueing system
3	SA support through 360° visual sensors	Maintaining SA through vision alone taxes one sensory modality.	Light Detection and Ranging (LIDAR)-to-tactile SA
4	Formation mobility supported through radio communication and teleoperation	Section- and platoon-level mobility will require teleoperation, increasing workload.	Formation adherence guides

2. Scientific Basis: Designing Interface Elements for Transparency

One of the key issues in improving human-autonomy teaming is supporting transparent interaction between the human and agents. Transparent interactions occur when others understand the actions, intentions, goals, and general reasoning of each team member. Agents facilitate this understanding by communicating their actions, the rationale behind those actions, and the outcomes of those actions with their human counterparts (Chen et al. 2014). Human-autonomy interfaces can be designed to convey this information, supporting transparent interaction. In this section, we describe the development of interface elements for supporting transparency and how they were implemented in the WMI.

2.1 Transparency and the SAT Model

HAT Project 2's transparency concepts are guided by the Situation Awareness-based Agent Transparency (SAT) model (Chen et al. 2014). Researchers have proposed several methods to determine the information that systems need to convey in order to facilitate a transparent interaction with them (Lyons 2013; Zhou et al. 2016). The SAT model delineates what information should be conveyed from an agent to its human teammate to improve agent transparency in order to support the human's situation awareness (Endsley 1995). Each level of the SAT model corresponds to a level of situation awareness, facilitating the human's understanding of an autonomous agent's actions, reasoning, and projected outcomes. The SAT framework enables a developer to identify what information should be conveyed to a human teammate in order for the human to comprehend the agent's intent and/or goals, the underlying rationale behind these actions, the expected outcomes of these actions, and the agent's confidence in projecting these outcomes. An agent that facilitates awareness of its own inner workings adds information to its human counterpart's explicit knowledge of the mission operation space, adding relevant information that would not be available otherwise. This added information, consequently, allows human teammates to extend their overall situation awareness to include their agent teammate. Further development of the SAT model expanded this idea of agent transparency to encompass agents with greater autonomous capabilities, supporting transparent interaction for both human and agent teammates, focusing on how bidirectional communications can be used to support this mutually transparent interaction (Chen et al. 2018). While the SAT model is used to identify what information should be conveyed to the human, how that information is conveyed is dependent on the type of agent interface, shared tasking demands, and the type of information.

2.2 The SAT Model as a Guide to Making Systems Transparent

The SAT model delineates the type of information that an autonomous agent should share with human teammates, which would, in turn, help the human understand the actions, intentions, and goals of the agent, as well as its reasoning process and expected outcomes (Chen et al. 2014). As described in Table 1, goals refer to the agent's objectives, actions describe what the autonomy is actually doing, and intentions refer to what the agent has chosen to do (Rao and Georgeff 1995; Klenk et al. 2013; Chen et al. 2014). When autonomous agents are designed to provide this information to their human counterparts, humans have better situation awareness of the agent and improved task performance outcomes while reducing the cognitive workload of the human teammate. One example is the design of a human-agent interface for an autonomous vehicle (Selkowitz et al. 2017a). This interface displayed the autonomous vehicle's goals during mission execution through the use of icons in an at-a-glance module (Selkowitz et al. 2017b). When the agent selected a different goal, the at-a-glance module changed icons. In this manner, the autonomous vehicle was able to communicate real-time goal changes in response to a dynamic environment.

Autonomous agents have an underlying reasoning process that enables independent goal selection (Chen et al. 2014). While reasoning processes may differ between agents, a common issue is that they do not necessarily convey this reasoning information to humans working with the autonomy. This opacity can divorce humans from the systems they work with, leading to deleterious outcomes (Chen and Barnes 2014). When humans are teamed with autonomous agents, the addition of reasoning information to the human-agent interface has been shown to have positive effects for the team (Chen et al. 2018). When humans were teamed with an autonomous vehicle, adding reasoning information to the interface resulted in the humans having greater trust in the agent (Boyce et al. 2015) and confidence in their situation awareness (Selkowitz et al. 2017a). Participants who worked with an intelligent route-planning agent had improved performance, shorter decision times, and demonstrated less complacent behavior when the agent shared the reasoning information behind its suggestions (Wright et al. 2017). Participants who partnered with an intelligent decision aide during the planning phase of a mission had more correct and fewer incorrect decisions when reasoning information was included than when it was not (Mercado et al. 2016). Clearly, there is substantial evidence as to the utility of conveying the agent's reasoning behind its actions and suggestions to their human teammates.

Human-autonomy teams often complete missions in complex, dynamic environments. These missions typically comprise a planning component, an execution component, and an after-action review component. Each of these components have different requirements, and so, the way in which autonomous systems can support transparent human-autonomy teaming for each of these components will differ as well. The decision aide that Mercado (2016), Stowers (2016), and their respective associates worked with is one such example of a planning system. While these studies used a number of both textual and visual interface elements to convey relevant information to the human operator, one particular visual element seemed most useful when comparing plans on a number of different factors. The comparison element, based off of Behymer and associates' (2015) Pareto efficiency approach to data visualization, presented interface users with a graphical display showing different parameters relevant to the mission. Those parameters were presented in columns, in which column order and width corresponded to that parameter's prioritization and weight, respectively. This kind of approach could also be used to convey autonomy's goals or the factors it used in its underlying reasoning.

Providing information pertaining to an autonomous system's underlying reasoning can also serve as a firm base onto which projections of future outcomes can be built. Combining reasoning information and projection of future information has been shown to yield improved operator performance on a shared decision-making task (Stowers et al. 2016). When using a comparison display as described previously, competing plans can be compared by mapping them onto each column, with higher placement in the column corresponding to a variety of rating systems. For example, higher placement on a column could mean that the plan better fits the need espoused by the column, that the plan has an increased likelihood of success based on that factor, or that the plan has the most examples of the element described by the column. As long as the rating is used across all columns, the visualization is a very intuitive approach to laying out a series of variables for comparison.

2.3 Transparency and Cueing

Transparent interfaces face the difficulty of not just presenting information, but presenting that information in such a manner so that users will attend to it. Many of the transparency concepts described previously presented targeted information visually in order to improve human understanding of the autonomy. The NGCV WMI, however, not only includes multiple data streams presenting complex information simultaneously (which the autonomous team members react to when changes are made in those streams) but also includes channels by which a crew member can pilot a vehicle from within a vehicle in a different location.

Visually monitoring several screens over extended periods is a cognitively demanding vigilance-type task that imposes high workload demands on an operator (Körber et al. 2015). Over time, the crew could begin to experience a vigilance decrement (Hancock and Warm 1989), resulting in crew members missing agent-supplied information or overlooking a change in status. Augmenting the interface with a cueing system that alerts the user when the agent presents updated information has been shown to improve performance and increase user trust in the system (White et al. 2009; Mercado et al. 2014). When the agent-supplied information is presented visually, supporting this information with cues presented in a separate modality (e.g., auditory or tactile) informs the user without adding to their cognitive load or further taxing their attentional resources (Wickens 1980, 1991). Prior research has demonstrated the addition of cues in a separate modality than that which the primary task is presented improved task performance and decreased response time (Hancock et al. 2013; Mercado et al. 2014).

2.4 Spatial Orientation Concerns in NGCV Operations

In addition to response times, the experience of controlling one vehicle from inside another is expected to present specific challenges to accurate localization, especially as the distance among vehicles in the unit increases. Modern military units report contact with the enemy in terms of the three D's (distance, direction, and description), which can present localization problems as the azimuth and distance are relative to the reporting unit. Klatzky (1998) provides operational definitions of egocentric (i.e., location of something relative to the observer) versus allocentric (i.e., location of something relative to something else) spatial representations. Based upon radio communication of the three D's, each listener must translate the called target's location from an allocentric spatial representation to an egocentric representation (though for the sake of parsimony, it is worth noting that authors have made the convincing argument that these representations are not pure forms, but rather dominated by one type of representation or the other; Ekstrom et al. 2014). These spatial representations are well studied, and performance using them is known to vary between individuals (Wen et al. 2013), covary with impaired memory (Weniger et al. 2011) and post-traumatic stress disorder (Smith et al. 2015), and strategies involving them change in response to acute stress (Van Gerven et al. 2016). For these reasons, guaranteed accurate localization using the baseline WMI requires visual attention to the map display, which can divert crew members' attention from other vital tasks. Alternatively, an intelligent cueing system can provide each crew member with individually tailored spatial localization information to improve their ability to maintain awareness of the vehicle's actions and positioning.

3. Conclusion

One of the goals established by the HAT ERP is to demonstrate an improvement in Soldier understanding of the NGCV's actions, intentions, goals, and general reasoning. In order to meet that goal, we are leveraging the WMI and other resources of the MEL-SIL to develop transparency concepts for the NGCV that will demonstrate these improvements. The final interface will be developed over the course of four iterations, guided by the principles of transparent human-autonomy interaction. Ultimately, the final product will be delivered to CCDC GVSC for testing in their motion platform-equipped simulator and, as feasible, integrated into the US Army's fielded NGCV.

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List of Symbols, Abbreviations, and Acronyms

ANVEL	Autonomous Navigation Virtual Environment Laboratory
ARL	Army Research Laboratory
CCDC	US Army Combat Capabilities Development Command
DCS	Direct Contract Services Inc.
DP	decision point
ERP	Essential Research Program
GVSC	Ground Vehicles System Center
HAT	Human-Autonomy Teaming
INFORMS	Information for Mixed Squads
LIDAR	Light Detection and Ranging
MCV	Manned Combat Vehicle
MEL-SIL	Manned-Unmanned Teaming Experimentation Laboratory, Simulation in the Loop
NGCV	Next Generation Combat Vehicle
optempo	operations tempo
RCV	Robotic Combat Vehicle
RTK	Robotic Technology Kernel
SA	situation awareness
SAT	Situation Awareness-based Agent Transparency
TRP	Transparent Route Planner
WMI	Warfighter Machine Interface

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875 N RANDOLPH STREET
BLDG 87
ARLINGTON VA 22203-1986

1 USA NSRDEC
(PDF) RDNS D D TAMILIO
10 GENERAL GREENE AVE
NATICK MA 01760-2642

1 OSD OUSD ATL
(PDF) HPT&B B PETRO
4800 MARK CENTER DRIVE
SUITE 17E08
ALEXANDRIA VA 22350

12 CCDC ARL
(PDF) FCDD RLH
J LANE
Y CHEN
P FRANASZCZUK
K MCDOWELL
A MARATHE
B PERELMAN
FCDD RLH BD
D HEADLEY
FCDD RLH FA
A DECOSTANZA
FCDD RHL FB
A EVANS
FCDD RLH FC
J GASTON
FCDD DAH C
L GARRETT
FCDD DAH W
F MORELLI