NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

AC/323(AVT-255)TP/1041

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STO TECHNICAL MEMORANDUM **TM-AVT-255**

Findings of the AVT-255: Unmanned Systems Mission Performance Potential for Autonomous Operations

(Conclusions de l'AVT-255 : potentiel d'exécution de la mission des systèmes sans pilote destinés aux opérations autonomes)

This memorandum describes the results and findings of the AVT-255 RTG.

This document contains the timeline of the AVT-255, the limited results, and the RTG's recommendations for future research.

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and the RTG's recommendations for future research.

The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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Findings of the AVT-255: Unmanned Systems Mission Performance Potential for Autonomous Operations

(STO-TM-AVT-255)

Executive Summary

Unmanned Systems (UMS) play an increasingly vital role in NATO military operations and will form a large part of the fighting forces of the future. However, due to the rapidly advancing technologies used in UMS, very few standards exist in terms of how UMS performance is measured. This is particularly true in the case of autonomous performance. This lack of agreed-upon definitions and test methods has greatly hindered the use of UMS in full-scale NATO operations. Therefore, an urgent need exists to provide users with a tool for not only defining a UMS's level of autonomy but also quantitatively measuring the impact of autonomy on UMS mission performance.

Recognizing this need, the AVT-175-RTG: Unmanned Systems (UMS) Platform Technologies and Performances for Autonomous Operations was formed. This RTG defined the technologies impacting autonomy and autonomous performance, presented a comprehensive overview of current UMS systems in use by NATO countries for potential military applications, and provided an exhaustive review of the current test methods, standards, autonomy definitions, and autonomous performance assessment tools in use today. The scope of the AVT-175's efforts were somewhat limited by the lack of data related to full-scale operations at higher levels of autonomy, as autonomous UMS have yet to be fielded extensively for NATO missions. This report is available through the NATO RTO.

In light of the technology, test methods, and autonomous performance method reviews, the AVT-175 developed a new tool for predictively assessing contextual autonomous performance, the Mission Performance Potential (MPP). The current effort, the AVT-255 "Unmanned Systems Mission Performance Potential for Autonomous Operations," sought to implement the MPP in software and validate the code using field testing of autonomous UMS operations.

However, the AVT-255, even after a one year extension, was not able to achieve its goals.

The unsuccessful completion of the AVT-255 can be attributed to three reasons:

1) The primary code developer had to withdraw from the effort.
2) The validation field tests were cancelled.
3) The AVT-255 research grew outdated.

This memo provides a detailed explanation of the AVT-255 timeline and limited results, and goes on to recommend next steps for testing and evaluation of autonomous UMS.

Conclusions de l'AVT-255 : potentiel d'exécution de la mission des systèmes sans pilote destinés aux opérations autonomes

(STO-TM-AVT-255)

Synthèse

Les systèmes sans pilote (UMS) jouent un rôle de plus en plus crucial dans les opérations militaires de l'OTAN et formeront une grande partie des forces de combat à l'avenir. Néanmoins, en raison de l'évolution rapide des technologies des UMS, il existe très peu de normes pour mesurer les performances, en particulier dans le cas d'un fonctionnement autonome. Ce manque de conventions sur les définitions et les méthodes d'essai a largement entravé l'utilisation des UMS dans les opérations de l'OTAN à pleine échelle. Par conséquent, il est urgent de fournir aux utilisateurs un outil qui non seulement définisse le niveau d'autonomie des UMS, mais qui mesure quantitativement l'impact de l'autonomie sur l'exécution de la mission de l'UMS.

L'AVT-175-RTG « Technologies et performances des plateformes de systèmes sans pilote (UMS) destinés aux opérations autonomes » a été formé pour répondre à ce besoin. Ce RTG a défini les technologies ayant un impact sur l'autonomie et le fonctionnement autonome, présenté une vue générale des UMS actuellement utilisés par les pays de l'OTAN dans des applications militaires potentielles et fourni une revue exhaustive des méthodes d'essai, normes et définitions de l'autonomie et des outils d'évaluation du fonctionnement autonome aujourd'hui en usage. La portée des travaux de l'AVT-175 a été quelque peu limitée par le manque de données concernant les opérations en grandeur réelle à des niveaux élevés d'autonomie, car la mise en service des UMS autonomes n'a pas encore été généralisée dans les missions de l'OTAN. Le présent rapport est disponible auprès de la RTO de l'OTAN.

À la lumière des technologies, méthodes d'essai et revues des méthodes d'exécution des missions, l'AVT-175 a mis au point un nouvel outil destiné à évaluer de manière prédictive le fonctionnement autonome dans le contexte ou « potentiel d'exécution de la mission » (MPP). Les travaux de l'AVT-255 « Potentiel d'exécution de la mission des systèmes sans pilote destinés aux opérations autonomes » cherchaient à mettre en œuvre le MPP dans un logiciel et à valider le code par des essais sur le terrain sous la forme d'opérations autonomes d'UMS.

Cependant, l'AVT-255, même à l'issue d'une prolongation d'un an, n'a pas atteint ses objectifs.

L'échec de l'AVT-255 peut être attribué à trois raisons :

1) Le principal développeur du code a dû quitter le projet.
2) Les essais de validation sur le terrain ont été annulés.
3) Les recherches de l'AVT-255 ont été peu à peu dépassées.

Ce mémo fournit une explication détaillée de la chronologie de l'AVT-255 et des résultats limités, puis émet des recommandations sur les étapes à suivre pour tester et évaluer des UMS autonomes.

FINDINGS OF THE AVT-255: UNMANNED SYSTEMS MISSION PERFORMANCE POTENTIAL FOR AUTONOMOUS OPERATIONS

1.0 THE NEED FOR PERFORMANCE MEASURES

It is impossible to accurately determine a UMS's mission performance without testing the UMS in the field. Determining performance is further complicated by the fact that a UMS could be used for multiple missions, each with different tasks and environments. Several methods for assessing UMS performance and autonomy level have been proposed, and details on these methods can be found in the final report document of the AVT-175: Performance Measures for Unmanned Systems RTG [1]. While each method has its own strengths and weaknesses, none of them address the core problem proposed by the AVT-255 of determining:

1) UMS's mission performance; and
2) The impact of autonomy on mission performance.

While the previously proposed tools provide a sound theoretical basis for addressing the problem of quantifying autonomy, none of these tools address the more practical need for tool to determine the mission-specific fitness of a UMS.

A contextual performance tool that can predict mission performance potential without full scale testing would provide the critical tool missing in the UMS evaluation process. Without full scale, in-theatre testing, the true mission performance of a UMS cannot be accurately determined. Therefore, a tool that predicts potential for a particular mission given the UMS hardware, software, and operational environment is needed. Specifically, a new tool should be developed that provides the following:

- A single, numeric value, that is comparable between UMS systems and provides a predictive measure of UMS performance for a given mission, environment, and autonomy level.
- A fixed UMS autonomy level by which UMS performance is measured.
- An input data set that can be evaluating using only the UMS system and mission description.

1.1 The AVT-175

The AVT-175 set out to create the above-described single-number metric to predict autonomous UMS performance as a function of autonomy level, mission, and environment. In this task, the RTG was successful. The AVT-175 released the following products: a new performance measure for unmanned systems, the Mission Performance Potential (MPP), a technical report, and an alpha version of the MPP software (available upon request). However, this version of the software is viable only for unmanned aerial system assessment, and accurate performance is not guaranteed. This memo presents below a few brief details on the AVT-175 activity.

1.1.1 The AVT-175 Results

The original goal of the AVT-175 workgroup was to develop procedures for the assessment of system mission performance as a function of platform autonomy for unmanned land, sea, and air vehicles. The group accomplished this by developing a new performance assessment tool that predicted platform performance for a given mission at a given autonomy level: the Mission Performance Potential (MPP). The AVT-175 developed the MPP by first performing an in-depth review of all the currently accepted and proposed metrics for UMS autonomy and performance. In light of these current methods, the AVT 175 developed two new methods for performance assessment: the Non-Contextual Autonomous Performance (NCAP) and general intelligence metrics. These new methods, along with the existing research, were then leveraged to create the MPP.

The development of a new framework was necessary because the then-current methodologies were insufficient, particularly in terms of defining a UMS's performance for its mission or range of missions. Many of the existing tools required extensive field-testing to compute autonomy level or autonomous performance. Many of the existing tools also required well-defined metrics descripting the UMS's environment and mission. Furthermore, while these tools measured autonomy level, they did not provide an answer for the impact of autonomy level on mission performance.

The MPP works by taking data related only the UMS platform hardware, software, and intelligence and combining this data using fuzzy logic rules derived from the mission profile. The MPP starts from a pre-defined autonomy level and predicts the UMS performance for its mission at that level of autonomy. The MPP methodology removes the two major barriers preventing performance assessment of UMS: the need for field-testing and the need for detailed, standardised environment and mission metrics. Furthermore, the MPP was actually implemented and calculated for two example UMS, moving from the theoretical world to the practical. Actual computation via software is a key step that was, at the time, missing with many other proposed methodologies and frameworks.

1.1.2 The MPP

At its core, the MPP is similar to previously proposed performance assessments that can be found in the literature. The MPP leverages the work already done in other efforts and reframes these ideas into a new framework, specifically one that addresses mission-specific performance potential. While based on previous efforts, the MPP is unique in several ways:

- The MPP can be calculated using only data related to the UMS platform and does not depend on field-testing results.
- The MPP does not compute an autonomy level but rather fixes the UMS autonomy level.
- The MPP defines a potential for mission-specific performance, not an assessment of performance, i.e., the MPP provides an idea of the maximum possible performance of a UMS system for a given mission.
- The MPP value is calculated using fuzzy logic along with other uncertain reasoning techniques, and the specific rules for the fuzzy aggregation of the MPP are defined using the mission description.

Using fuzzy logic, the MPP aggregates all the necessary data related to the UMS system (hardware, software, intelligence) into a final MPP score. This allows the MPP to handle qualitative data related to the UMS while also making the MPP extensible to any mission and environment profile. Instead of being tied to a set of metrics that must be measured for the mission and environment, as with the ALFUS [2], the MPP handles only those metrics important to the given mission.

Figure 1 shows a high-level view of the MPP. Data are collected similar to the data collected for the NCAP or intelligence metrics. Then, the MPP uses questions related to the mission and environment to create 'masks' with which to score the UMS. For example, if a mission requires a UGV to operate in soft-soil conditions, the MPP will automatically be set to zero for any UGV that cannot operate in these conditions, regardless of its level of autonomy or performance in other areas. This is a major benefit of the MPP over previous methods.

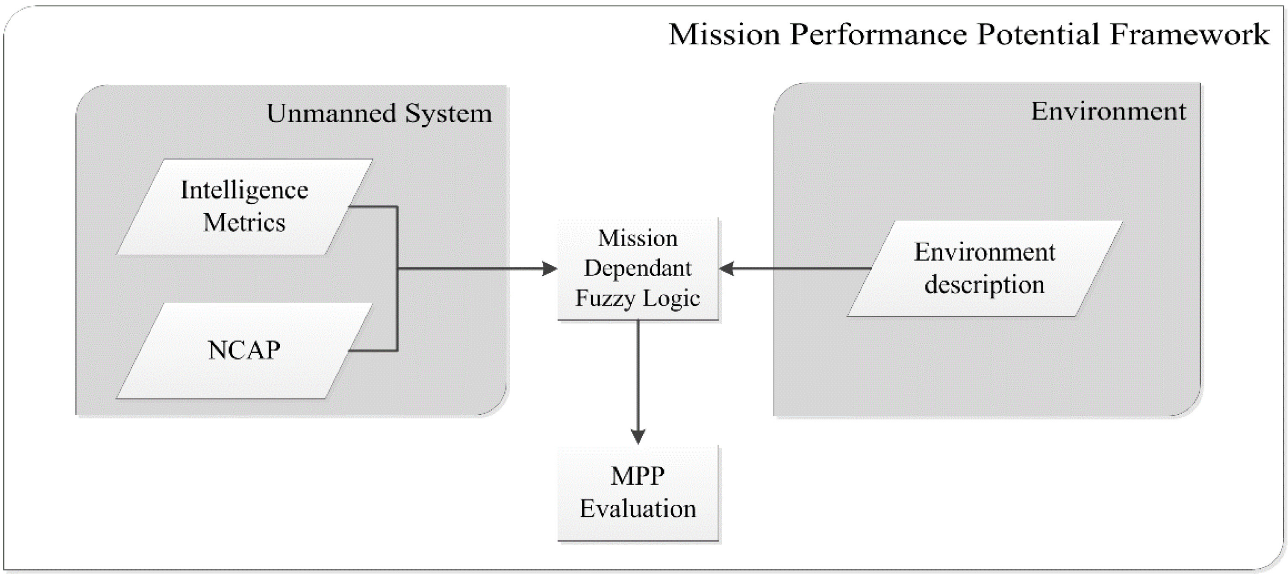

Figure 1: The MPP Framework.

1.2 Conclusions

At the time of its release, the AVT-175 products were of great interest to the NATO UMS community. Therefore, it made sense to continue this research. The goal was to create a follow-on RTG to continue validating and developing the MPP software. The AVT-255 hoped to move the MPP software from "alpha" to "release 0.5." The RTG also hoped to validate the MPP concept against maritime and ground operations. Unfortunately, the AVT-255 was not successful in these goals.

The following section provides the goals and timeline of the AVT-255, from inception to dissolution. Section 3.0 goes on to explain why the AVT-255 was unsuccessful, and Section 4.0 gives recommendations for how to pivot the AVT-255 findings into relevant future research.

2.0 THE AVT-255 PROPOSAL AND TIMELINE

2.1 The AVT-255 Proposal

The goal of the AVT-255 was to realise the MPP software, validate this software for all UMS domains (air, sea, ground), and distribute the software, with users' guide, to the AVT Panel.

For reference, an abbreviated copy of the AVT-255 Technical Activity Proposal (TAP) and Terms Of Reference (TOR) is presented below.

2.2 The AVT-255 Technical Activity Proposal (TAP) (Abbreviated)

Table 1: The AVT-255 TAP.

<table>
<tr><td>ACTIVITY REFERENCE NUMBER</td><td>AVT-</td><td rowspan="2" colspan="2">ACTIVITY TITLE

Unmanned Systems Mission Performance Potential for Autonomous Operations</td><td>APPROVAL
TBA</td></tr>
<tr><td>TYPE AND SERIAL NUMBER</td><td>RTG</td><td>START
1/2016</td></tr>
<tr><td colspan="2">LOCATION(S) AND DATES</td><td colspan="2">In conjunction with AVT Panel Business Weeks</td><td>END
12/2018</td></tr>
<tr><td colspan="2">COORDINATION WITH OTHER BODIES</td><td colspan="3">None</td></tr>
<tr><td colspan="2">NATO CLASSIFICATION OF ACTIVITY</td><td>UNCLASSIFIED/UNLIMITED</td><td colspan="2">Non-NATO Invited
Yes</td></tr>
<tr><td colspan="2">PUBLICATION DATA</td><td>TR</td><td colspan="2">NU</td></tr>
<tr><td>KEYWORDS</td><td colspan="4">Unmanned Systems, Autonomy Level, Mission Performance, Environment</td></tr>
</table>

I. BACKGROUND AND JUSTIFICATION (Relevance to NATO):

The AVT-175 workgroup explored procedures for the assessment of system mission performance as a function of platform autonomy for unmanned land, sea, and air vehicles. They discovered that current methodologies were insufficient in defining an Unmanned Systems (UMS) mission performance or autonomy level. Based on this discovery, the workgroup developed two new methods for performance assessment: the non-contextual autonomy potential and the intelligence metrics. The workgroup used these methods to develop a new performance assessment tool that predicts platform performance for a given mission at a given autonomy level. This assessment tool is called the Mission Performance Potential (MPP) and is described in the Technical Report of the AVT-175.

As recommended in the Report, the MPP will require substantial refining, testing, and validation before it can be used to its full potential. The AVT-175 recommends that a follow-on RTG activity be established to pursue the refinement and validation of the MPP.

NATO Relevance:

a) Safety and Security requirements of the NATO Units engaged in Peace Keeping.

b) Peace-Holding missions may be satisfied by an increasing use of Unmanned Systems.

c) Critical Infrastructure Protection (DAT #10).

d) The development of a Unified Methodology leading to Standardised Performance Metrics will impact the LCC of UMS.

II. OBJECTIVE(S):

Refine the question tables, data collection for UMS, and the fuzzy logic methodology to finalise the MPP algorithms. Validate the MPP algorithms against actual data from UMS testing, competitions, and in-theatre deployments. This validation would make the MPP a powerful tool for UMS assessment, mission planning, and UMS design.

III. TOPICS TO BE COVERED:

Perception, Intelligence, Environment, Platform, and Communication are the primary topics to be covered in reference to developing and validating the MPP.

IV. DELIVERABLE (e.g., Model, Database, …) AND/OR END PRODUCT (e.g., Final Report):

Model.

2.3 The AVT-255 Terms of Reference (TOR) (Abbreviated)

Terms of Reference (ToR)

AVT-255 / XXX / RTG)

ON

Unmanned Systems Mission Performance Potential for Autonomous Operations

I ORIGIN

A. Background

The AVT-175 workgroup explored procedures for the assessment of Unmanned Systems (UMS) mission performance as a function of platform autonomy for unmanned land, sea, and air vehicles. They discovered that current methodologies were insufficient in defining an unmanned systems mission performance or autonomy level. Based on this discovery, the workgroup developed two new methods for performance assessment: the Non-Contextual Autonomy Potential (NCAP) and the intelligence metrics. The workgroup used these methods to develop a new performance assessment tool that predicts platform performance for a given mission at different autonomy levels. This assessment method is called the Mission Performance Potential (MPP) and is described in the Technical Report of the AVT-175.

As recommended in the 175 Technical Report, the MPP will require substantial refining, testing, and validation before it can be used to its full potential. The data used for input into the MPP algorithms, including data about the UMS hardware system, UMS intelligence metrics, and mission parameters, needs to be further studied and defined. The fuzzy mathematical methods and non-Boolean logics used to compute the overall MPP value need to be studied further and iteratively refined to determine the best algorithms for predicting mission performance. The MPP output performance predictions then need to be validated against UMS field-testing for a wide range of NATO operationally relevant platforms and missions. Therefore, the AVT-175 recommends that a Research Task Group (RTG) be created to pursue the further development, refinement, validation, and ultimate distribution of the MPP tool.

The MPP development must be done through the RTG as the research topic is very broad. Collaboration must be realised across multiple international partners to share the critical information about UMS hardware platforms, software intelligence, performance characteristics, and field-testing data needed to validate the MPP. NATO partners must also take ownership of the MPP software tool to ensure it is developed in such a way as to impact design, development, testing, and fielding of UMS assets for NATO missions.

B. Justification (Relevance for NATO)

A validated MPP will benefit both military and industry users across NATO across a wide range of activities, both in the short term and long term. The immediate benefits of the MPP are:

1) *A standard definition for autonomy levels for UMS and a metric for how this autonomy level impacts mission effectiveness;*
2) *An agreed upon framework for how UMS performance is assessed, that will allow comparison between UMS assets of NATO nations;*
3) *A groundwork for standardised data organisation/presentation for UMS systems engineering data and field-testing data, as well as¸ a mechanism for sharing this data between NATO nations.*

The MPP will also have long-term benefits to NATO:

1) *Peace-holding missions may be satisfied by an increased use of UMS;*
2) *Increased mission performance prediction of multi-type UMS across a broad range of systems resulting in improved mission success rate;*
3) *Enhanced assessment of needed R&D investments based on the relation of autonomy/intelligence with mission performance capability and cost of an UMS;*
4) *The potential use of the MPP as a design tool for decision making early in the UMS design process when cost is low and risk is high (i.e., exploring the change in expected mission performance via MPP calculation when changing sensor, platform, intelligence parameters);*
5) *Increased ability to utilise teams of UMS/increased levels of UMS cooperation.*

II OBJECTIVES

The RTG will continue the work of the AVT-175 by refining the question tables, the data collection formats for UMS, and the fuzzy logic methodology to finalise the MPP algorithms. It will verify and validate the MPP algorithms against actual data from UMS testing, competitions, and in-theatre deployments. This validation will make the MPP a powerful tool for UMS assessment, mission planning, and UMS design. The goal is to provide NATO with an MPP computer model that will be described in a technical report. It is estimated that 3 years will be required to collect data, refine the algorithms, verify, and validate the MPP methodology, create the computer model, and publish the technical report. The deliverables of the proposed RTG are summarised below:

1) *A refined, standardised set of data and question tables for input into the MPP methodology;*
2) *A validated, enhanced fuzzy logic algorithm for computed the MPP value;*
3) *An MPP software tool;*
4) *A final technical report / "user manual".*

2.4 The AVT-255 Timeline

The timeline of the AVT-255 is as follows:

2014: The AVT-175 publishes its report.

2015: The MPP is presented at the AVT-241: Applications for Future Military Operations Specialists' Meeting.

2016: The AVT-255 officially begins.

2017 (spring): Original AVT-255 co-chair steps down from NATO activities.

2017 (fall): Key AVT-255 members step down from NATO activities.

2018: Lead software developer steps down from NATO activities.

2019: The AVT-255 officially concludes.

2021: This memo is published.

This timeline provides a frame of reference for the AVT-255. To understand the progression of the group, it is of upmost importance to understand the value the UMS community placed in autonomy metrics in 2016. From 2010 – 2018, the UMS community was focusing a large amount of energy towards creating something like the MPP. The community was seeking a "magic bullet" single-number metric that measured autonomous performance. Thus, coming into 2015 and the inception of the AVT-255, research into the MPP was considered critical to the success of NATO UMS operations. For various reasons, this research fell out of favour and relevance over the course of the ABT-255 (this topic is saved for discussion in Section 3.0).

This timeline gives insight into the breakdown of the AVT-255. Firstly, the goal of the AVT-255 was to validate the MPP metric against field tests in multiple domains. To date, the MPP has only been validated using unmanned aerial vehicles. As such, the first year of the AVT-255 was spent planning tests with unmanned surface vehicles for naval interjection missions. The data collection plan was completed, and steps were taken to update the MPP software during this year. However, by the second year of the AVT-255 these tests had been cancelled. Furthermore, no additional tests were planned by member nations, leaving the group unable to validate the MPP.

Secondly, the AVT-255 sought to improve upon the MPP software. However, the lead software developers also had to withdraw from the AVT-255, leaving the AVT-255 without core developers for the MPP software code. Furthermore, the MPP software was to be translated from MATLAB code to Python, an undertaking that required computer programming experience beyond the remaining team members.

Third, and finally, the autonomous performance assessment community moved on from single-metric measures of performance during the 2018 – 2021 timeframe. The testing community has proposed and adopted new measures of autonomy during the last 2 – 3 years. Not only that, the very idea of "autonomy" has changed, and the UMS mission set has grown into new, more complicated applications. Thus, while the concepts created by the AVT-175 and continued by the AVT-255 are not without merit, further work on these tools will be a little impact to the current UMS community.

2.5 Summary

The evolution of the RTG over 2016 – 2019 provides an interesting account of the advancement of UMS. In 2016, autonomous systems were fielded in a very limited capacity. Most UMS were small (< 50 kg), and almost all were teleoperated. The focus of UMS performance research at the time was aimed at understanding how advancing from teleoperation to autonomous operation would affect mission performance. It must be remembered that at the time, autonomy for UMS was largely error-prone and ineffectual. Making a UMS "smarter" often made a UMS *less* successful at its mission. A means of quantifying that fact was necessary.

Today, years of experience with UMS have provided the community with a better understanding of UMS capabilities. The need to quickly encapsulate UMS performance diminished as increasing numbers of UMS were fielded for NATO operations. Likewise, the advancement of Machine Learning (ML) algorithms introduced a level of autonomy the AVT-255 could not have predicted.

It stands to reason, then, that even without the setbacks described above, the AVT-255 products themselves would be outdated today. While the AVT-255 did not meet its stated goals, it is not appropriate to also say that it produced no viable results. Sometimes research that fails teaches us just as much as research that succeeds. The AVT-255 gives a first-hand account of how quickly UMS technologies are advancing. The AVT-255 also introduced concepts that have taken hold within the UMS community. The following section provides details on the positive outcomes of the AVT-255.

3.0 THE AVT-255 RESULTS AND FINDINGS

As the first two sections have discussed, the AVT-255 did not produce what its TAP and TOR promised; however, it did still produce results of value to the NATO UMS community. The AVT-255 did succeed at broadening the knowledge of UMS testing and evaluation. The attempt to realise the MPP had the following positive impacts to the UMS community:

- Novel ways of measuring UMS performance using fuzzy logic.
- Novel ways of measuring Sensor-Environment Interactions (SEI).
- Novel software for aggregating test results into a single-number metric.

These impacts are described below.

3.1 Fuzzy Logic for Quantifying Test Performance

The AVT-255 continued to explore the use of intelligent computation and fuzzy logic for performance assessment. UMS, especially autonomous UMS, are inherently "fuzzy" systems. Additional factors affect autonomous operations beyond those that affect traditional vehicle platforms. Rather than hardware-based concerns, the outputs of the UMS autonomy algorithms and perception algorithms will determine its ultimate mission effectiveness.

Therein lies the problem. Hardware performance is easily measured; algorithm performance much less so. Hardware will behaviour the same across tests. Autonomy algorithms will not. There is no reason to expect an obstacle detection algorithm to always detect an obstacle the same way. Likewise, a path planning algorithm will not choose the same path around the obstacle every time.

Measuring UMS performance is challenging because it's hard to quantify a UMS that "usually" avoids an obstacle, or "mostly" turns right instead of left. Therefore, the AVT-255 demonstrated that performance metrics must be abstracted beyond binary pass/fail and/or strict quantification metrics.

Fuzzy logic makes use of so-called "membership functions": each variable has some degree of membership within a set of values. A variable's degree of membership to a set is a qualitative measure of similarity to members of that set. This sets fuzzy logic apart from percentages and statistics. Fuzzy logic is the different between a liquid that has a 90% chance of being water and a liquid that has 0.9 degree of membership to the set of liquids containing water. A very good overview of the basic nature of fuzzy logic can be found in Ref. [3].

Using the nature of fuzzy logic, UMS performance can be "fuzzified." A measure of performance could be something like a turning performance of 0.6 degree of membership to the set of "sharp turns." The general "fuzzification" of UMS performance takes place as:

1) General observations about the UMS are made.
2) These observations are turned into qualitative performance measures, i.e., "somewhat sharp turning."
3) The qualitative performance measures are broken down into set membership functions.
4) The membership functions are aggregated trough fuzzy logic methods.
5) The aggregated metrics are "de-fuzzified" to provide a quantitative metric.

The "de-fuzzification" process turns a degree of membership back into a single number. This process can take place in many ways following a set of context-based rules. At its heart, de-fuzzification is an aggregation operator. It is a mathematical process through which several degrees of membership are combined into a quantity. The MPP software uses several methods of de-fuzzification.

This fuzzy logic assessment process remains the first of its kind proposed for UMS testing. As mentioned before, prior testing methods focused on hardware benchmark testing. These types of tests yield finite numerical values. On the other hand, fuzzy logic provides an ability to assess the inherent randomness in UMS performance. The AVT-255 provided a proof-of-concept that fuzzy logic methods could be superior for assessing autonomous UMS performance in the future.

The AVT-255 has generated several new studies in this field, including Refs. [4], [5], and [6].

3.2 Sensor-Environment Interaction and Mission Performance as a Function of Environment

Prior to the AVT-175, vehicle performance was largely measured as a function of hardware performance. Testing included how fast the platform could travel, how steep a slope it can climb, etc. However, the efforts of the AVT-255 proved that Vehicle-Environment Interaction (VEI) were *not* the limiting factor in UMS autonomous performance. In fact, as mentioned above, it is ultimately the impact of the environment on perception algorithms that determines performance.

With the advent of autonomy, VEI is no longer the sole deciding factor in performance. Now, vehicles must both physically navigate the environment *and* sense and understand the environment. An autonomous UMS cannot operate in a world it does not understand. In the case of autonomous UMS, the Sensor-Environment Interaction (SEI) will define performance. Therefore, the AVT-255 showed that the next generation of performance assessment will have to include both VEI and SEI.

SEI can be broken down into:

1) The hardware properties of the sensors (range, field-of-view, etc.).
2) Fuzzy environment definitions ("some" rain, "dense" vegetation).

3) The properties of the autonomy algorithm (localisation within *x* cm of accuracy).
4) The measurement of performance of the algorithm as a function of the environment (range and accuracy in rain).
5) The measurement of the performance of the UMS as a function of algorithm performance (sensor sees *x* distance, resulting in *y* algorithm accuracy, resulting in *z* UMS action).

SEI resides within the MPP process by defining the de-fuzzification rules. The UMS hardware and software performance fall within some fuzzy range of values. As the AVT-175 proved, these performance values are heavily influenced by the environment. For autonomous UMS, the environment/SEI defines final performance. Therefore, environmental factors are defined and then used inside the MPP software to "de-fuzzyify" performance metrics.

As an example, take an unmanned ground vehicle operating off-road. There are many capable UGV platforms available. Using traditional metrics, a UGV with excellent on-road performance would score higher than a UGV with poor on-road performance. However, the second UGV is more suited to the mission. Traditional performance measures would encourage mission planners to use the first system, when, in fact, the second would be more effective.

The fuzzy logic used in the MPP addresses this very problem. By defining a mission-level performance based on the environment, the more capable UGV would be given a higher MPP value. The MPP software does this by setting environment-based rules. In this case, the performance metrics for on-road performance would be greatly diminished in performance, or possibly even excluded all together. In this case, the rule would be something to the effect of "if rough terrain performance less than *x*, MPP defaults to *0*."

The following section gives some brief details on the MPP software itself, including its use of fuzzy logic.

3.3 The MPP Software

The alpha version of the MPP software was developed and transitioned to the AVT-175 and AVT-255 group members. This version is written in MATLAB. While the software is not fit for transition to projects outside very basic research, it still gives an example of how performance measurement software can be created and how fuzzy logic can be used for UMS performance assessment.

Table 2 shows an example of MPP input data – the physical hardware properties for a UMS – for the MPP. It contains the basic properties required to calculate a MPP score, as described in Section 1.0. Figure 2 shows the MPP software interface for inputting these data. Similarly, Figure 3 and Figure 4 show the interface for inputting environment and sensor performance parameters.

These figures show the difference between the MPP and other UMS performance metrics at the time. While most measures were retroactive and assessed a level of autonomy at which the UMS *performed*, the MPP measure was predictive, and assessed how well a platform *would perform* based on its hardware, software, and level of autonomy. Table 2 and Figure 3 and Figure 4 show the basic parameters needed to calculate the MPP score.

For an example MPP calculation, Figure 5 shows the input parameters for a notional UAV. If one parameter is set to a value outside the mission requirements, say by increasing the amount of rainfall in the environment, the MPP automatically sets the MPP to *0*, as shown in Figure 6. The fuzzy nature is shown in the values between *0.0 – 1.0* (i.e., sensor resolution and sensor accuracy). Rather than defining a finite performance, they define a degree of membership to the set of ideal sensors with perfect accuracy.

Table 2: Example Physical Parameters Related to the UMS Platform that Would Feed into the MPP Software Algorithms.

Parameter	Description	Estimation Approach	Input Value Interval	Output Value	Comments	Application Domain
Weight	The total weight of platform in (kg)	Single numerical value	0 – max (predetermined constant)	Small, Medium, Large	The output value is got via process called "fuzzification", which allows transformation of numerical values into linguistic values. Linguistic values afterwards are used inside the reasoning mechanism. Knowing the max values, the linguistic values can be generated automatically.	UGV, UAV
Ground clearance	Distance from the bottom of the platform to ground surface in (m)	Single numerical value	0 – max (predetermined constant)	Small, Medium, Large	The same	UGV, UAV
Height	Height	Single numerical value	0 – max (predetermined constant)	Small, Medium, Large	The same	UGV, UAV
Width/ wingspan	Width	Single numerical value	0 – max (predetermined constant)	Small, Medium, Large	The same	UGV, UAV
Length	Length	Single numerical value	0 – max (predetermined constant)	Small, Medium, Large	The same	UGV, UAV

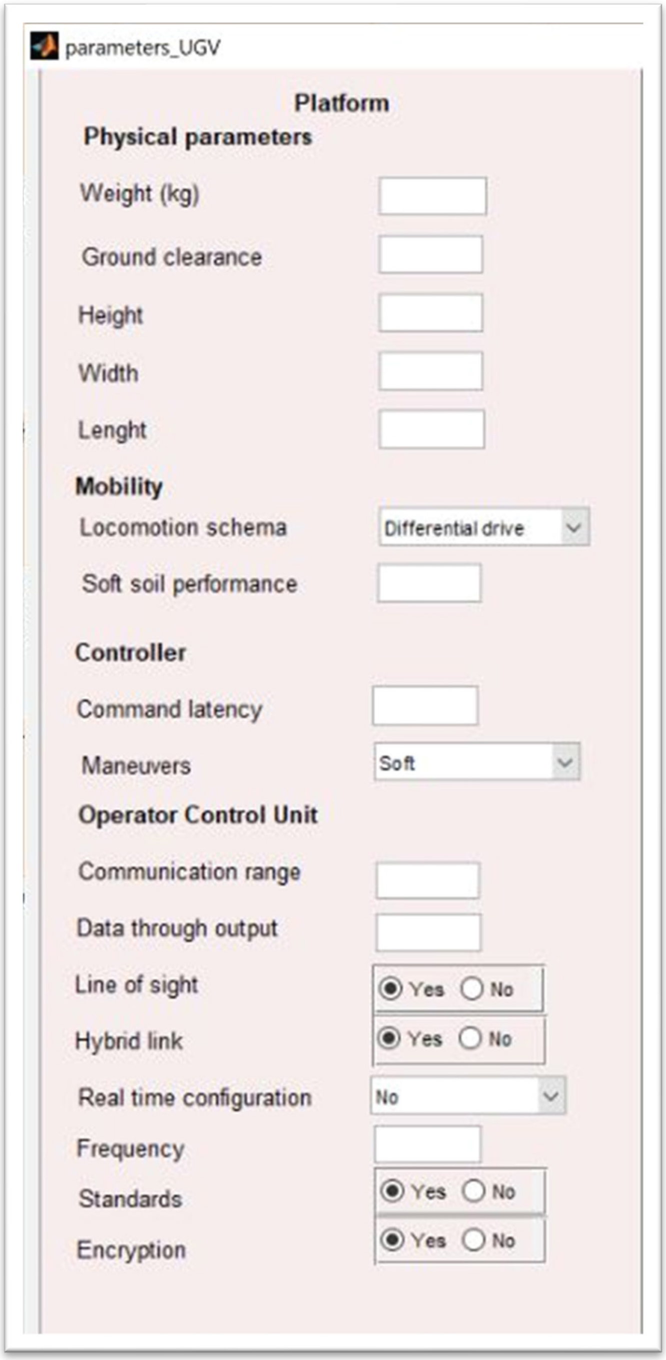

Figure 2: The MPP Software Input Screen for Inputting UGV Platform Hardware Metrics.

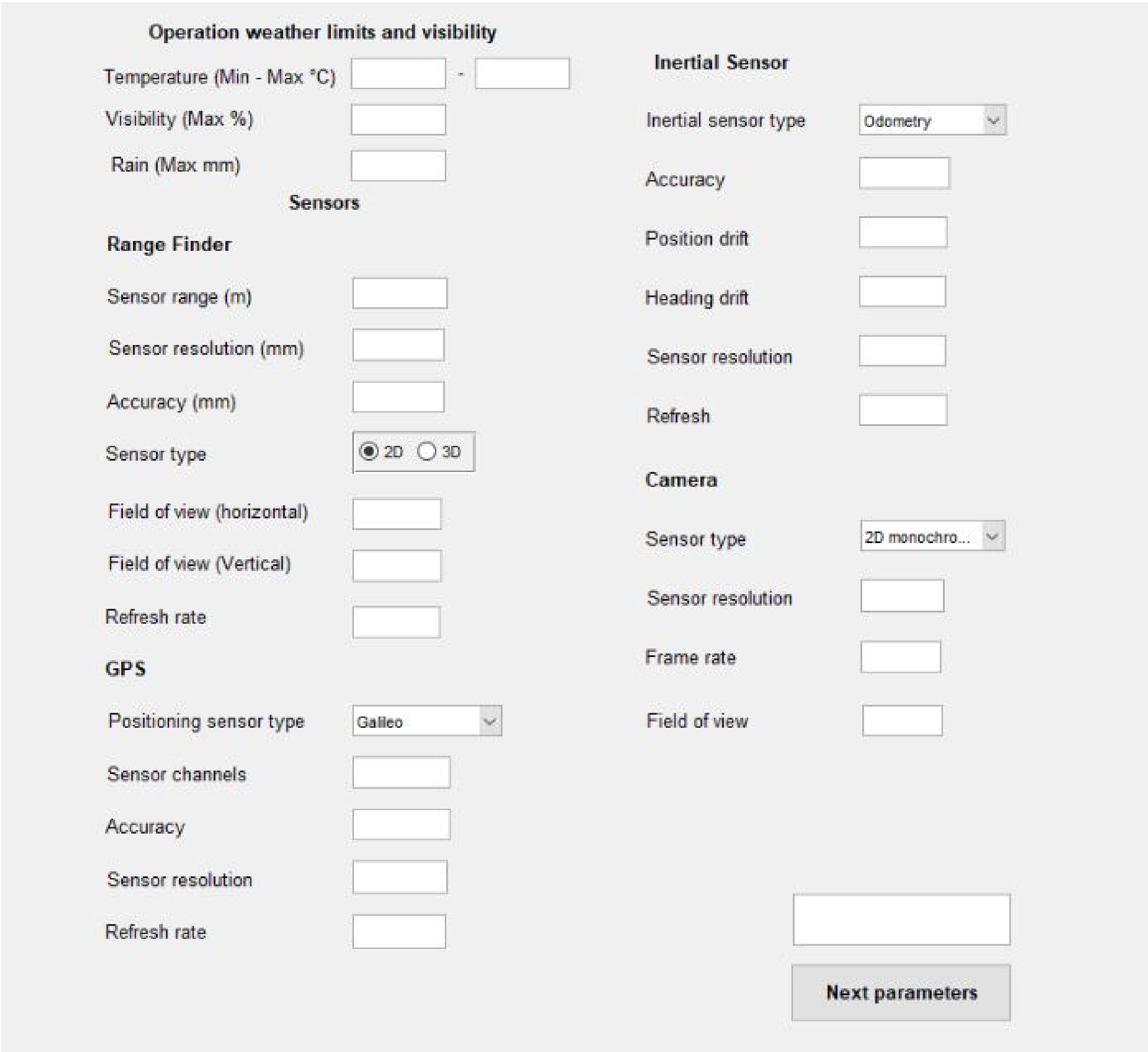

Figure 3: The MPP Software Input Screen for Inputting Environment and Sensor Metrics (1/2).

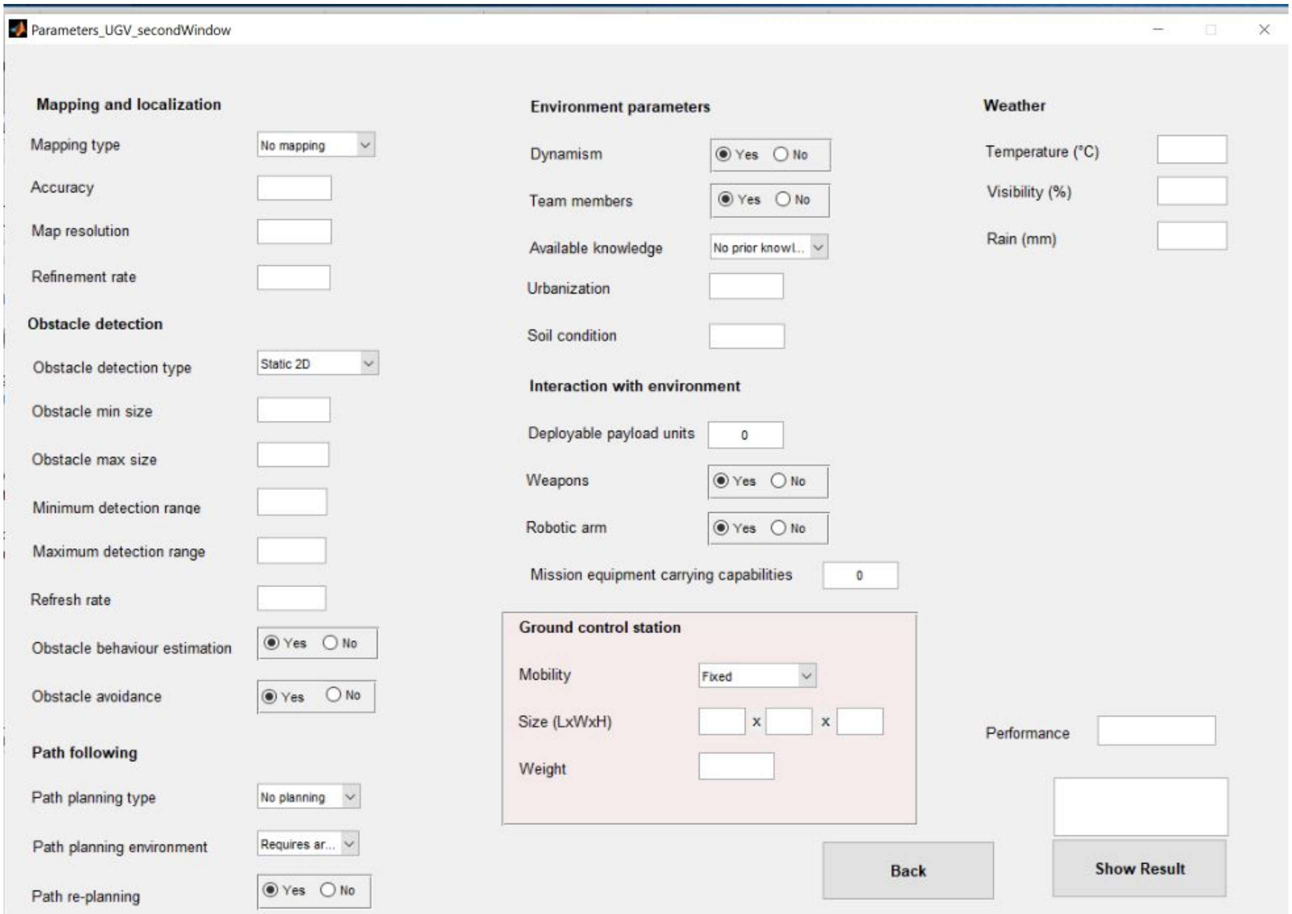

Figure 4: The MPP Software Input Screen for Inputting Environment and Sensor Metrics (2/2).

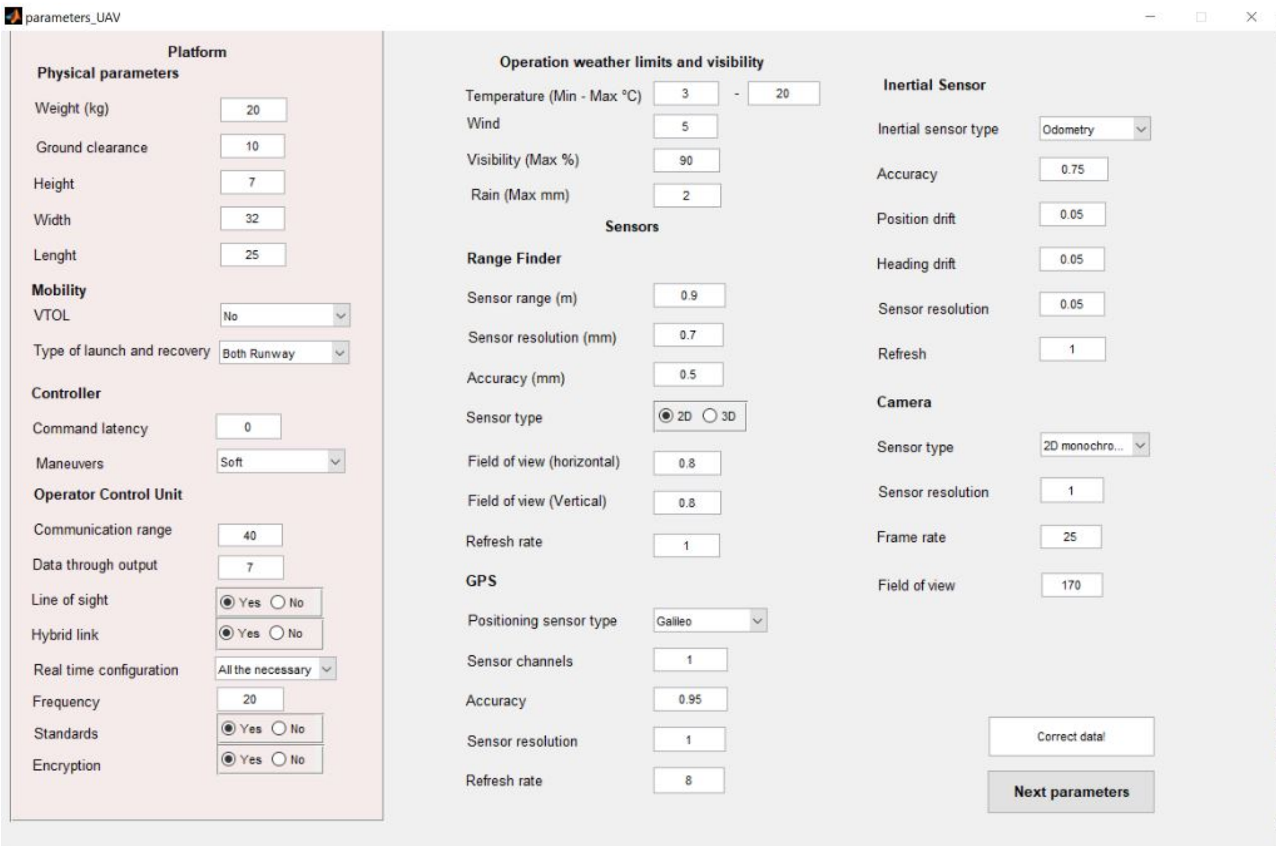

Figure 5: Input Data for a MPP Calculation for a Notional UAV.

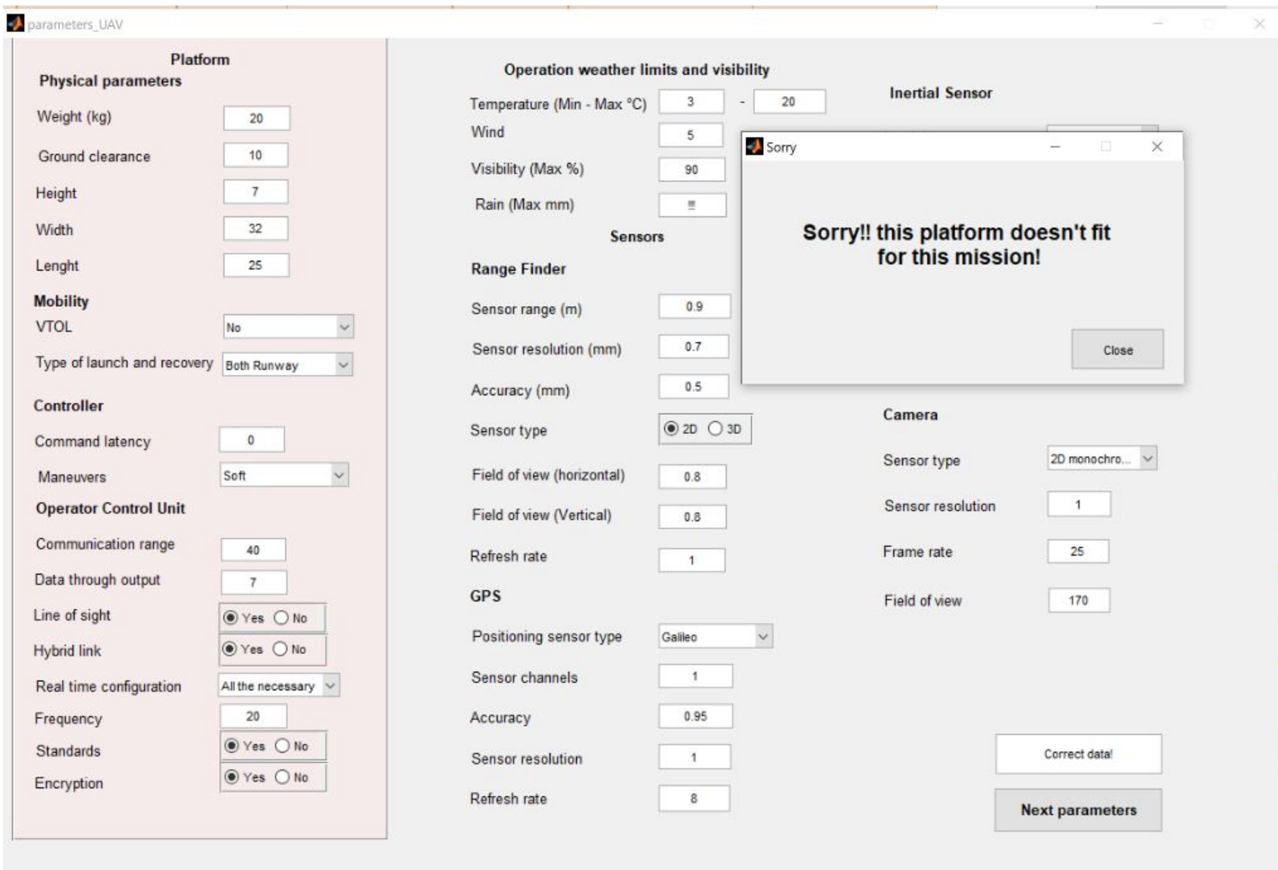

Figure 6: The MPP When Environment Parameters Exceed Hardware/Software Performance.

3.4 The MPP and Machine Learning

One key concept not yet discussed in this report is the current rise in Machine Learning (ML) algorithms. While ML was never part of the AVT-255 scope, it is worth noting that ML is, like autonomy, a fuzzy science. ML algorithms defy typical performance measures, such as accuracy or success percentage. Additionally, performance assessment of ML has not been addressed in any standardised way to date. ML for autonomous UMS has a very "wild west" feels, with new algorithms being leveraged for new applications at a break-neck pace. This rapid advancement mirrors, in many ways, the rapid advanced of autonomy algorithms in the 2010 – 2020 timeframe.

All this to say, the core methodology of the MPP can potentially be extend to ML for autonomous UMS. The broader UMS community understands that traditional performance measures fall short of capturing the capabilities of ML. Therefore, a further potential side product of the AVT-255 is a conversation starter in the burgeoning field of performance assessment for ML. More on this follows in Section 4.0.

3.5 Summary

The AVT-255 ultimately did provide several meaningful deliverables to the AVT and UMS community. The AVT-255 further examined fuzzy logic for UMS performance. Indeed, in the interim years after the AVT-255 to today, the study of fuzzy logic for performance assessment has enjoyed great attention across the UMS community. The AVT-255 also introduced the concept of SEI. SEI remains a very new concept in the UMS community, and members of the AVT-255 are striving to disseminate this idea across the UMS community (see the recommendations for future work found in Section 4.0).

Moreover, the AVT-255 produced a slightly enhanced version of the MPP software. Despite its many flaws, this software remains the only of its kind. As the UMS community moved beyond single-number measures of autonomous performance, no other tools for *actually* measuring performance have been developed. In this way, the AVT-255 marked a benchmark in UMS performance assessment as a proof-of-concept that such a software could, in fact, be created. While further development of the core MPP software is highly unlikely, some pieces of it, in particular the fuzzy logic functions, will possibly find further life in the UMS community.

4.0 RECOMMENDATIONS AND FUTURE RESEARCH

As Section 3.0 shows, the results of the AVT-255 help shine a light on what comes next for UMS performance assessment. The recommended next steps in UMS performance assessment are as follows.

4.1 The State of Autonomy for UMS

"Autonomy" has become a fluid concept. Many UMS execute different parts of their mission at different levels of autonomy. A single number metric simply cannot predict UMS performance. Moreover, the need for standard levels of autonomy has been met, to an agreeable extent, by the Society of Automotive Engineers (SAE) agreed upon levels of autonomy [7]. However, a common understanding of how to test "autonomy" is still needed. This is especially true regarding the "autonomousness" of ML algorithms.

ML has fundamentally changed autonomy. Indeed, a memory of the original problem the AVT-175 addressed is becoming visible again. The current concept of assessing ML algorithm performance is nebulous, at best. What is worse, comprehensive assessment of ML algorithms is innately impossible. Even to its authors, ML code is still a "black box." The overall success rate can be measured but measuring the root cause of failures is not always possible.

The AVT-255 approach to measuring autonomous performance could potentially be extended to ML. Like autonomy, ML is inherently fuzzy. It might by the case that measuring ML membership functions and rulesets proves useful as performance metrics.

Another challenge facing the UMS testing community is the concept of SEI as a limiting factor to performance. Prior to autonomy, performance assessment took place at the hardware level. The interaction of the physical platform with the world determined its performance. This is not the case for autonomous systems. One key finding of both the AVT-175 and AVT-255 still stands today: a platform that *can* cross a ten-foot gap *cannot* cross a ten-foot gap it doesn't perceive.

Therefore, agreed upon ways of quantifying SEI and UMS performance as a function thereof are necessary. As with ML, the testing of environmental factors looks more like a "soft" science than an assessment tool. The testing community lacks metrics for defining environments, which in turn hinders the development of UMS requirements. Indeed, it is hard to ask for a system that operates in a certain environment when you have no measure of what said environment actually is.

4.2 Recommendations

In light of the findings of the AVT-255 contained in this document, the AVT-255 concludes by making the following recommendations.

1) The UMS community has largely moved past defining levels of autonomy or autonomous performance. Given this fact, the AVT-255 finds that future work on definitions, frameworks, and ontologies for autonomy and autonomous performance assessment are of limited value. The mindset of autonomy for UMS and testing of UMS has changed greatly in the last decade, and the AVT community no longer needs universal standards and definitions across all domains and applications.

2) The AVT community needs a better understanding of how to test ML technologies for UMS. No matter how useful ML algorithms for autonomy are, they cannot be fielded until they can be thoroughly tested. Currently, no quantitative metrics exist for evaluating ML for UMS applications. However, a tool in the same spirit as the MPP, i.e., one relying on fuzzy logic, could meet this assessment need. Therefore, this report recommends the creation of a new AVT activity to examine how, if at all, the UMS community measures ML performance. Specifically, the AVT-255 recommends hosting a Specialists Meeting to bring together ML experts to share information on their test methods.

3) The AVT community also needs to explore the impact of SEI on autonomous performance. SEI is the future of VTI research, and SEI will increasingly become the limiting factor in autonomous UMS performance. Ways of quantifying environmental conditions are lacking, i.e., how to measure rainfall, vegetation, etc. This lack is currently hindering the advancement of SEI research. Furthermore, this lack makes building a shared knowledge of UMS testing difficult. The final recommendation of this report is the creation of an ongoing AVT activity to collect, study, and curate the extant SEI test metrics, and build an ontology across the AVT regarding this new type of performance testing.

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Findings of the AVT-255: Unmanned Systems Mission Performance Potential for Autonomous Operations

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This memorandum describes the results and findings of the AVT-255 RTG.
This document contains the timeline of the AVT-255, the limited results, and the RTG's recommendations for future research.

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14. Abstract

The AVT-175 workgroup explored procedures for the assessment of unmanned system mission performance as a function of platform autonomy for unmanned land, sea, and air vehicles. They discovered that current methodologies were insufficient in defining an Unmanned Systems (UMS) mission performance or autonomy level. The AVT-175 developed a new performance assessment tool that predicts platform performance for a given mission at a given autonomy level. This assessment tool is called the Mission Performance Potential (MPP) and is described in this report. The AVT-255 workgroup sought to further validate the MPP tool by executing validation experiments and updating the MPP software. Unfortunately, the AVT-255 was not able to achieve this goal because 1) Many key members dropped out early in the effort; and 2) The AVT-255 research did not yield significant results. Indeed, assessments of UMS have changed greatly over the last five years, making the core MPP product less valuable to the military UMS community than it was in 2016. To that end, this memo provides the history and timeline leading up to the AVT-255, the limited results of the workgroup, and recommendations for future work in the area of autonomy testing, evaluation, and assessment.

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