A Planning Pipeline for Large Multi-Agent Missions

Meghan Chandarana
Autonomous Integrated Systems
NASA Langley Research Center
Hampton, VA, USA
meghan.chandarana@nasa.gov

E. L. Meszaros
Dept. of Egyptology and Assyriology
Brown University
Providence, RI, USA
e.l.meszaros@brown.edu

B. Danette Allen
Autonomous Integrated Systems
NASA Langley Research Center
Hampton, VA, USA
danette.allen@nasa.gov

***Abstract*—In complex multi-agent applications, human operators are often tasked with planning and managing large heterogeneous teams of humans and autonomous vehicles. Although the use of these autonomous vehicles broadens the scope of meaningful applications, many of their systems remain unintuitive and difficult to master for human operators whose expertise lies in the application domain and not at the platform level. Current research focuses on the development of individual capabilities necessary to plan multi-agent missions of this scope, placing little emphasis on the integration of these components in to a full pipeline. The work presented in this paper presents a complete and user-agnostic planning pipeline for large multi-agent missions known as the HOLII GRAILLE. The system takes a holistic approach to mission planning by integrating capabilities in human machine interaction, flight path generation, and validation and verification. Components – modules – of the pipeline are explored on an individual level, as well as their integration into a whole system. Lastly, implications for future mission planning are discussed.**

Keywords–pipeline; multi-agent; mission planning; human-machine interaction; validation and verification.

I. Introduction

As autonomous robotic vehicles grow increasingly ubiquitous, their use in applications like search and rescue and science data collection increases. As a result, the expertise of human operators shifts from that of system level domain experts to that of application level experts. In complex multi-agent missions these application level experts are human operators who are tasked with planning and managing heterogeneous teams of agents composed of humans, Uncrewed Aerial Vehicles (UAVs), ground rovers, etc. The use of autonomous vehicles as tools increases the ability of operators to perform tasks that are beyond their current capabilities, yet these tools remain difficult to operate as they are based on unintuitive existing systems. Fixing this, however, requires the generation of a user-agnostic and comprehensive mission planning tool that allows for intuitive mission specification by any human operator.

Prior research has focused on optimizing or instantiating many individual components of this mission planning pipeline, but often fails to take into account the components as a whole and their integration into a complete pipeline. Existing work on this topic is also published across a number of different disciplines, making the process of integrating these individual components more difficult. This project focuses on the need for a cohesive pipeline that unifies individual components, allowing for successful and trusted mission planning by human operators in multi-agent teams. By demonstrating the feasibility of a full pipeline, this work innovates on advancements made to individual components.

This paper evaluates the full pipeline by which a human operator would plan a mission and define objectives, thereby allowing the system to interpret this into actionable directions. The current instantiation of this pipeline is HOLII GRAILLE: Human Operated Language Intuitive Interface with Gesture Recognition Applied in an Immersive Life Like Environment. By presenting individual components, this paper proposes a system capable of both mission planning and supervisory control during execution. We specifically focus on UAV mission planning where operators are tasked with defining vehicle flight paths.

Current research in to the development of individual components necessary to build a mission planning pipeline are outlined in Section II. Planning tools and methods for eliciting desired information from human operators are examined as a necessary component of an optimal mission planning pipeline (Section III). Different modalities of interaction are also considered for accurately capturing the intent of mission specification and general usability. A planning tool aid for determining mission parameters, such as swarm size, is outlined in Section IV. The captured data are then fused with dynamic environmental information to produce an accurate and flyable plan, as described in Section V. Section VI presents how flight paths are displayed to the human operator using virtual or augmented reality tools, allowing for iterative modification and verification methods. Once plans have been fully verified, agents can leverage established behaviors to carry out the prescribed goals. To realize a fully successful system performance, all of these individual components must partner synergistically for the creation of a cohesive mission pipeline, or the HOLII GRAILLE of mission planning systems. The full pipeline is tested on a scaled-down indoor mission in Section VII, and its implications are further discussed in Section VIII. Suggestions for continued research efforts that build upon this holistic design are considered in Section IX.

II. Background & Related Work

Current research efforts in multi-agent planning primarily focus on the low level vehicle planning. These methods range from manual interfaces that require human operators to explicitly define the paths of each vehicle individually to fully autonomous interfaces that calculate the vehicle trajectories automatically using mission parameters. Common autonomous planning frameworks include Markov Decision Processes (MDPs) [1], game theoretic frameworks [2] and integer programming frameworks [3], and typically use reward functions to shape the solution.

In addition to vehicle path planning, numerous research efforts have focused on mission planning interfaces. A large number of these choose to adopt gesture and speech input

modalities. These modalities are used to mimic natural human-human communication patterns and thereby reduce operator workload [4]. Cauchard et al. showed that human operators prefer to interact with autonomous agents in the same way they would with another human [5]. Ng and Sharlin explored a gesture interface for collocated vehicles [6]. In [7] and [8], users defined flight paths directly using a speech-based and 3D spatial interface respectively. Gesture-based interfaces often rely on full body movements [9] or static hand poses to program by demonstration [10]. Bolt et al. use a multimodal interface to manipulate a graphical user interface [11]. Suárez Fernández et al. designed a flexible multimodal interface framework which allowed users to choose the input modality based on their application [12]. These methods failed to examine how multimodal interfaces could be adapted for multi-agent mission planning. In addition, previous methods failed to explore more simplistic, unmounted sensors for gesture input.

Further focus has been placed on verifying and validating autonomous systems, which can often be difficult due to complex and non-deterministic behavior. Emphasis has been placed on ensuring the safety of not just the individual components of a system but their intricate interactions as well, further complicating the process [13]. Kamali et al. describe a method of verifying models of a system's behavior and interactions to complement a model checker algorithm to verify a system [14]. Li et al. developed a game theoretic approach to modeling autonomous vehicles for verification [15]. With the spread of autonomous systems, any methods for verification and validation have focused on incorporating measures of trust and trustworthiness as well. Though not explicit certification measures, aspects of trust inform how well the system will be utilized by human operators and are therefore crucial for evaluation. Lyons et al. lament that current verification and validation techniques do not take trust and trustworthiness into account, making them outdated at best [13]. One method for improving trust and working toward more robust verification and validation methods is through explainable AI (XAI), where efforts are made to ensure the explicability of outputs from complex systems [16].

Despite extensive research in multi-agent path planning algorithms, interfaces, and verification and validation techniques, little emphasis is placed on the design of a complete planning pipeline. Individual components are built without the full pipeline in mind. As a result, the complexities and additional requirements of pipeline integration are often neglected.

III. Human Machine Interaction

To effectively plan large scale multi-agent missions (i.e., large number of agents), human operators must begin by specifying both the high level mission objective(s) and necessary vehicle specifications (e.g., vehicle flight paths and/or collaborative behavior). Regardless of what the mission is and what tools are being exploited to carry it out, the system design must address two basic questions: how will necessary information be requested from the user, and through what means will the user be allowed to provide that information? These questions must be addressed in order for the eventual mission to be a success, but they can be addressed at an abstract level, regardless of how the multi-agent mission is instantiated.

The methods by which operators provide information to the system have been the focus of much second-wave human/computer interaction research, and available options are as varied as they are ubiquitous, ranging from touch-interfaces on smart phones and voice recognition on electronic assistants to simple point-and-click computer interfaces. Recent research suggests that using intuitive interfaces that make use of natural communication techniques helps to increase usability. Making an operator learn not just how to use a system but how to interact with that system in order to use it adds an additional barrier to use. Intuitive user interfaces often eschew the metaphorical interfaces with which many users are now familiar, such as the point-and-click and even the touch interfaces. Such interfaces provide a metaphorical extension of the finger or hand into the metaphorical desktop/page/window structure of the computer. As computing systems have evolved, this underlying metaphor has remained constant [17]. A switch to intuitive methods of communication that rely on human/human interaction models should relieve the user of extra training.

Figure 1. Human operator using the multimodal interface to define a mission.

Most current research, however, focuses on natural language as a way of tapping into intuitive human/human communication strategies. Verbal and even gestural interfaces are examined for their ability to allow operators to talk to systems in an intuitive manner. More intuitive, however, are multimodal interfaces that allow for a combination of different input types [18]. Combining different input modalities allows a system to account for characteristics that are difficult to identify with one modality of input – vehemence, intonation, sarcasm, etc.

The HOLII GRAILLE project used a multimodal interface comprised of speech and gesture modalities [19][20][21]. Users were able to provide necessary information by communicating to the system as they would another human counterpart, augmenting gestural information with spoken details and vice versa (Figure 1). Human operators used gesture inputs to specify the shape of trajectory segments, while speech inputs defined additional geometric information (e.g., length, radius, height). The gesture interface used a Leap Motion controller relying on three infrared cameras to track the motions of the user's palm. Users gestured over the controller in a set of defined motions that represented flight path segments. Simultaneously, operators voiced their commands into a headset, providing additional distance information to augment the gestured trajectory. These commands were translated into text using the CMU Sphinx speech recognition software and interpreted into additional flight data. All trajectory segments were then combined by way of the fused gesture and speech input data (Section V). This multimodal approach allowed HOLII GRAILLE a means of error checking; whenever data from the speech and gesture interface provided conflicting information, the system was able to determine identify and compensate

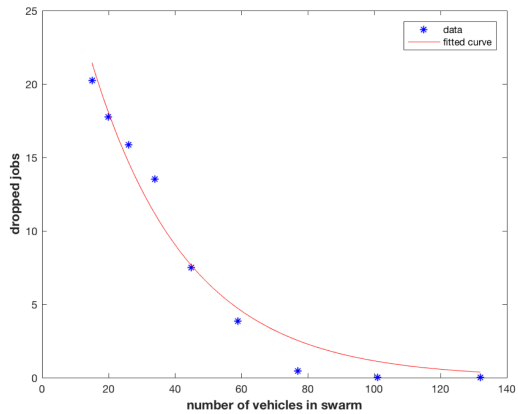

Figure 2. Example of predicted relationship between swarm size and the expected number of dropped jobs.

for the problem [21]. Future iterations of such multimodal interfaces can examine confidence levels in data coming from each interface in order to dynamically determine which one to trust in the case of discrepancy, and incorporate additional communication modalities within the multimodal interface.

IV. Mission Planning Tools

When planning large multi-agent missions, human operators are often tasked with defining additional system parameters such as the number of vehicles (i.e., the swarm size). In many multi-agent – swarm – missions, vehicles must service jobs of various types as they are sensed. For a myriad of applications these jobs must be immediately serviced or risk negative consequences. For example, failing to inspect a compromised bridge after a natural disaster may limit the evacuation routes out of a city. To successfully service the jobs, a small group of vehicles must break off from the main group for a specified amount of time. Each job type requires a different number of vehicles and service time to complete it. Typically, the expected job types and their associated resource requirements are known by the operator. However, in general, only the expected number of jobs of each type is known and not the explicit locations. This uncertainty poses an extremely challenging planning problem to human operators. Therefore, mission planning tools that can provide a predictive model of the steady state system performance must be developed. These models, when used as a reference, will allow human operators to effectively find a balance point in the complex trade-offs between mission parameters such that the desired system performance is met.

One method for modeling complex multi-job type missions is to leverage algorithmic queuing theory. If we assume that the swarm is analogous to a pool of servers, then the sensed jobs can be thought of as arriving customers. In this case, since the swarm itself is moving and the jobs are stationary, the arrival rate for jobs of each job type is simply the expected time between sensing new jobs of that type. Assuming a constant search velocity, the time is equated to the expected average distance between jobs. Jobs are assumed to be randomly and uniformly distributed throughout the search area and thus arrive according to a Poisson distribution. The steady state performance of the system can then be analyzed using an M/M/k/k queuing system, where there are k servers (i.e., vehicles in the swarm) and the allowed size of the queue is k

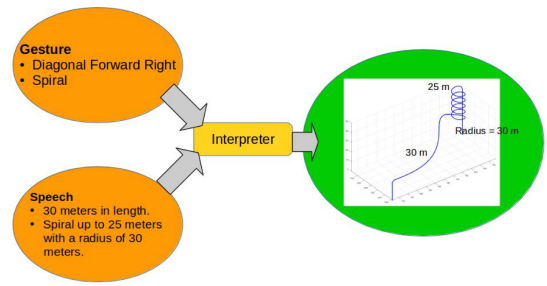

Figure 3. Example data that is fused together using the interpreter module.

(i.e., if not enough vehicles are left in the swarm to service a job the job is dropped). In [22] we show that the M/M/k/k model is able to accurately model multi-job type missions.

An M/M/k/k model is used to find the relationship between swarm size and expected number of dropped jobs given a set of job types and their associated parameters (i.e., required number of vehicles for service and service time). Figure 2 shows an example of the predicted relationship. The blue points show the analytical solutions, while the red line indicates the fitted curve. Depending on the application area, operators define different cost values associated with various parameters of the mission (e.g., vehicle cost, dropped job cost, etc.). These cost values allow operators to pinpoint where along the trade-off curve they should be to accomplish their desired system performance. By incorporating these prediction models as planning tools, systems like HOLII GRAILLE can reduce the workload on their operators while simultaneously improving overall system performance.

V. Mission Generation

Once a human operator has defined the mission objectives and parameters, the planning pipeline is tasked with using the high level mission specifications to define the low level vehicle commands required to successfully complete the mission. This is accomplished in two stages. First, all inputs given by the human operator are interpreted and fused together (Section V-A). The fused data is then sent to a trajectory generation module which uses the general mission specifications pertaining to the flight path to generate smooth and flyable (i.e., realizable with the vehicle controller) trajectories (Section V-B).

A. Interpreter

An interpreter module is used to fuse the gesture and speech data together for each trajectory segment that is defined using the multimodal interface. This is done by first synchronizing the data from the two input modalities. The data input order is preserved from each source by way of a stacked priority queue. Matched shape and geometric data are then paired by popping data off of their respective queues at the same time (Figure 3).

In HOLII GRAILLE's current instantiation of the interpreter module, when conflicting data is received from the gesture and speech inputs the priority queue framework allows the system to choose which input to take as true. This eliminates the possibility of any conflicting data being sent to the trajectory generation module. Future iterations of the interface can produce confidence values associated with the recognition of each input. The interpreter module would then use the confidence values to make a more informed choice

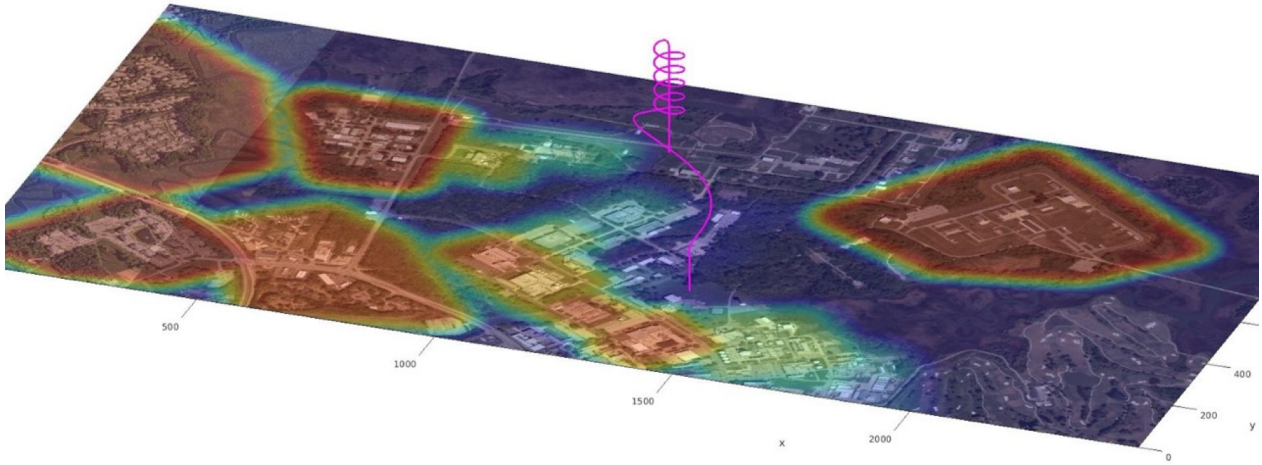

Figure 4. Example trajectory generated using human operator input combined with the expected risk map of the mission environment.

between the conflicting inputs. A weighted combination of the two inputs can also be used to improve overall system interpretation accuracy. If additional clarifying information is needed from the operator, the validation and verification step can be used to prompt the operator for this information. For example, if a conflict arises and the gesture input is chosen as the correct input, an operator may need to input the geometric information with the speech interface again so that the data collected matches the trajectory segment type that was defined using the gestures.

B. Trajectory Generation

Once the input data for each segment is fused together by the interpreter module, the trajectory generation module is then able to use the data to define the control points required to represent the segment with a Bézier curve. Each Bézier curve is a polynomial whose first and last control points are the start and end points of the curve. Therefore, the complete flight path is built in a piecewise manner by placing the individual curves in such a way as to ensure that the last point of the first curve is the same as the first point of the next curve. This also ensures at least C^0 continuity across the final combined curve. By extension C^1 and C^2 continuity can be guaranteed by placing the first and last two or three control points of each Bézier curve aptly. The details of this method for generating full piecewise Bézier curves is detailed by Mehdi et al. in [23].

In addition to generating realizable flight paths with guaranteed continuity, the HOLII GRAILLE framework leveraged known risk maps of the mission environment to ensure trajectories defined by human operators maintained a minimum risk level. If need be, the trajectory generation module modifies human operator generated flight paths to ensure that the level of risk for the mission stays below an allowed threshold. The risk maps used included areas with varying levels of risk (Figure 4). Risk values are shown as a color gradient from red to green. Red areas indicate no fly zones, while green areas represent areas of low risk. Blue areas on the map indicate no risk areas. A flyable trajectory with acceptable risk is shown in magenta. In this example mission, the human operator designed a trajectory which moved a UAV diagonally to a new point of interest and then moved the UAV in an upward spiral so that ozone measurements could be taken at varying altitudes over an area of interest. The trajectory generation module modified the diagonal segment to curve around the higher risk area shown in green.

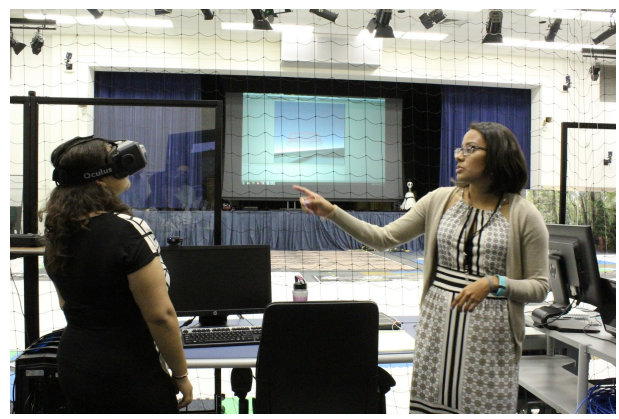

Figure 5. User models the VR headset used for verification and validation.

VI. Validation and Verification

After the interface collects information and the necessary trajectories are calculated, the final stage in the pipeline is validating and verifying the results. Displaying the developed flight path against a map of the environment and terrain can help the user evaluate whether obstructions have been properly avoided, and incorporating risk information about the environment allows the user to visualize if further avoidance measures should be implemented. A critical aspect of a functioning full system pipeline is the ability for the user not only to verify mission plans but, if necessary, to adjust them. Displaying collected and calculated information back to the user allows them an opportunity to correct for any errors and adjust for any new knowledge to be added into the system.

The HOLII GRAILLE pipeline displayed the calculated flight path through Virtual Reality (VR). Donning an Oculus headset and controllers, users were able to view the flight path in relation to the geographical environment, as well as risk maps, ensuring that the flight path stays within necessary physical parameters (see Figure 5). Moreover, the VR environment allows the flight path to be viewed from many different angles not limited to standard physical constraints. Similar functionality could be gained using augmented reality (AR), allowing the user to view the simulated flight path against

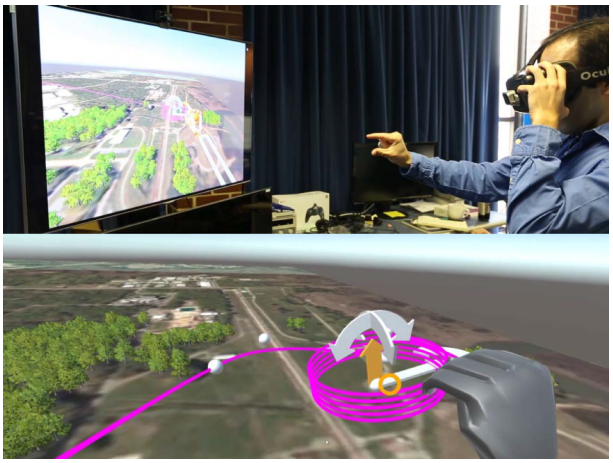

Figure 6. Human operator modifying vehicle trajectory using the VR headset in the verification and validation step [24].

a backdrop of reality, though this method requires physical presence in the geographical location of the mission. For ease and extension of use, VR was chosen in favor of AR modeling methods.

Ideally, VR environments also allow for easy and intuitive manipulation of the calculated flight path. Interacting with parameters of the mission as if they were physical objects within a shared environment means that the user can grab, pull, push, and stretch elements of a flight path in order to alter them, mirroring the gestural input modality used with the initial system interface (Figure 6). Not only does such manipulation make use of effective VR interactive strategies (see [25]) but it also allows for a continuation of input modality across the mission planning pipeline. Reliance on intuitive interaction strategies increase the general usability of this verification and validation system and suggest a potential broad user base for the end product.

VII. Results

The HOLII GRAILLE pipeline incorporates all of these individual components, generating the first complete pipeline for full mission management. To demonstrate its value, an indoor scaled-down demonstration of resulting trajectory formed using the complete HOLII GRAILLE pipeline was conducted (Figure 7). In the demonstration a human operator used the multimodal interface to define a desired trajectory and mission for the a UAV vehicle. The data was then sent to the interpreter module, which fused the data together. The trajectory generation module then utilized the risk map and the fused data to build a smooth and realizable flight path for the vehicle. After the flight path was created, the human operator was able to review the flight path using the VR headset. Once the operator had verified and accepted the generated trajectory, it was sent to the controller on board the vehicle.

During the demonstration, the risk map was projected using two overhead projects on the ground. A quadcopter was used to fly the scaled-down flight path over the projected environment – being sure to stay clear of the high risk areas. The flight path followed by the vehicle is shown in magenta. This demonstration indicated the value of a full, integrated pipeline, allowing non-expert users to easily take all the actions necessary to put autonomous vehicles to use.

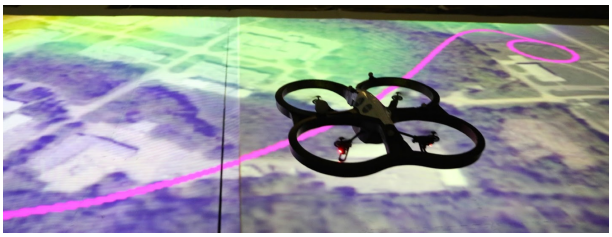

Figure 7. Scaled-down demonstration of a complete mission generated using the complete HOLII GRAILLE pipeline.

VIII. Discussion

Each individual component of the HOLII GRAILLE pipeline was designed with the human operator and full integration in mind. In doing so, the inputs and outputs of each component were easily identified. This also provided guidance on the internal design of the components. Additionally, by considering the human machine interaction from the start the system as a whole can push towards an increased level of trustworthiness with the human operator. HOLII GRAILLE may provide a path forward for increasing the usability of UAVs in critical domains as well as for establishing the basis for trust in and trustworthiness of these systems.

The HOLII GRAILLE pipeline is mission application agnostic, thereby allowing human operators to interact with the system in the same way regardless of their mission's objectives. The ease-of-use of the multimodal interface establishes a baseline for future execution interfaces. While this initial pipeline focuses on relatively straightforward mission specifications, the HOLII GRAILLE pipeline provides an initial design that can be modified in future iterations for more complex mission management. The interaction framework can be leveraged to develop mission modification capabilities. These execution interfaces will rely on the design and implementation of appropriate monitoring strategies that reduce the operator's overall workload [26]. In addition, for applications like search and rescue, to realize successful multi-agent missions on autonomous platforms additional behaviors, such as small team deployments, must be developed [27].

IX. Conclusion and Future Work

Having established a need for an intuitive, usable, and successful mission management tool, this paper discusses HOLII GRAILLE as one example of a full pipeline tool. With individual components working to increase usability and transparency of information, this mission management tools can work toward increasing successful interaction between application level experts and machines, as well as leading toward increased human operator trust in the system. By creating the pipeline from verified or verifiable components, the mission management tool provided a way to increase the overall trustworthiness of the system.

Future instantiations of a VR validation environment could make use of persistent simulations that continue to process information even when the user is not currently logged in [28]. Such a persistent environment could continue to recalculate risks, update information on weather, and process input from other users that would all contribute to an accurate modelling environment for the developed UAV flight path. Moreover, this environment does not have to rely on local information only and can incorporate data from a distributed network of users and inputs, further broadening the user base and

increasing access to flight path verification and validation [24]. With location-agnostic multiple user access, more users can be involved in the process of ensuring the flight path is fit and making modification if necessary.

Lastly, future iterations must take into account how the system lets the user know what information it needs. While methods of information elicitation were not examined as part of the HOLII GRAILLE pipeline, understanding how to elicit information from a human operator was looked at as part of the HINGE project [29]. While information elicitation is a moderately nascent focus for investigation, it is often incorporated in studies focused on situated human computer interaction and should be a focus for future pipeline iterations [30] [31].

Building upon these areas can allow future pipelines to address the management of more complicated missions. While HOLII GRAILLE provides an example multi-agent mission planning pipeline, future work focusing in these areas can help improve usability and lead to increased mission success.

Acknowledgment

The authors would like to thank the additional members of the HOLII GRAILLE team – Angelica Garcia, Lauren Howell, Jeremy Lim, and Javier Puig-Navarro – as well as the members of the Autonomy Incubator who contributed to the project.

References

[1] C. Guestrin, D. Koller, and R. Parr, "Multiagent planning with factored mdps," in Advances in neural information processing systems, 2002, pp. 1523–1530.

[2] G. Arslan, J. R. Marden, and J. S. Shamma, "Autonomous vehicle-target assignment: A game-theoretical formulation," Journal of Dynamic Systems, Measurement, and Control, vol. 129, no. 5, 2007, pp. 584–596.

[3] D. Bertsimas and R. Weismantel, Optimization over integers. Dynamic Ideas Belmont, 2005, vol. 13.

[4] L. Borin and J. Edlund, "Language technology and 3rd wave hci: Towards phatic communication and situated interaction," in New Directions in Third Wave Human-Computer Interaction: Volume 1-Technologies. Springer, 2018, pp. 251–264.

[5] J. R. Cauchard, J. L. E, K. Y. Zhai, and J. A. Landay, "Drone & me: an exploration into natural human-drone interaction," in Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing. ACM, 2015, pp. 361–365.

[6] W. S. Ng and E. Sharlin, "Collocated interaction with flying robots," in 2011 RO-MAN. IEEE, 2011, pp. 143–149.

[7] M. Quigley, M. A. Goodrich, and R. W. Beard, "Semi-autonomous human-uav interfaces for fixed-wing mini-uavs," in Intelligent Robots and Systems (IROS). Proceedings. 2004 IEEE/RSJ International Conference on, vol. 3. IEEE, 2004, pp. 2457–2462.

[8] N. Li, S. Cartwright, A. Shekhar Nittala, E. Sharlin, and M. Costa Sousa, "Flying frustum: A spatial interface for enhancing human-uav awareness," in Proceedings of the 3rd International Conference on Human-Agent Interaction. ACM, 2015, pp. 27–31.

[9] S. Waldherr, R. Romero, and S. Thrun, "A gesture based interface for human-robot interaction," Autonomous Robots, vol. 9, no. 2, 2000, pp. 151–173.

[10] J. Lambrecht, M. Kleinsorge, and J. Krüger, "Markerless gesture-based motion control and programming of industrial robots," in Emerging Technologies & Factory Automation (ETFA), 2011 IEEE 16th Conference on. IEEE, 2011, pp. 1–4.

[11] "Put-that-there: Voice and gesture at the graphics interface," vol. 14, no. 3. New York, NY, USA: ACM SIGGRAPH Computer Graphics, 1980, pp. 262–270.

[12] R. A. S. Fernández, J. L. Sanchez-Lopez, C. Sampedro, H. Bavle, M. Molina, and P. Campoy, "Natural user interfaces for human-drone multi-modal interaction," in Unmanned Aircraft Systems (ICUAS), 2016 International Conference on. IEEE, 2016, pp. 1013–1022.

[13] J. B. Lyons, M. A. Clark, A. R. Wagner, and M. J. Schuelke, "Certifiable trust in autonomous systems: Making the intractable tangible." AI Magazine, vol. 38, no. 3, 2017, pp. 37–49.

[14] M. Kamali, L. A. Dennis, O. McAree, M. Fisher, and S. M. Veres, "Formal verification of autonomous vehicle platooning," Science of Computer Programming, vol. 148, 2017, pp. 88–106.

[15] N. Li et al., "Game theoretic modeling of driver and vehicle interactions for verification and validation of autonomous vehicle control systems," IEEE Transactions on control systems technology, vol. 26, no. 5, 2018, pp. 1782–1797.

[16] N. Alexandrov, "Explainable ai decisions for human-autonomy interactions," in 17th AIAA Aviation Technology, Integration, and Operations Conference, 2017, p. 3991.

[17] S. A. Brasel and J. Gips, "Tablets, touchscreens, and touchpads: How varying touch interfaces trigger psychological ownership and endowment," Journal of Consumer Psychology, vol. 24, no. 2, 2014, pp. 226–233.

[18] E. L. Meszaros, M. Chandarana, A. Trujillo, and B. D. Allen, "Compensating for limitations in speech-based natural language processing with multimodal interfaces in uav operation," in International Conference on Applied Human Factors and Ergonomics. Springer, 2017, pp. 183–194.

[19] M. Chandarana, E. L. Meszaros, A. Trujillo, and B. D. Allen, "Analysis of a gesture-based interface for uav flight path generation," in Unmanned Aircraft Systems (ICUAS), 2017 International Conference on. IEEE, 2017, pp. 36–45.

[20] E. L. Meszaros, M. Chandarana, A. Trujillo, and B. D. Allen, "Speech-based natural language interface for uav trajectory generation," in Unmanned Aircraft Systems (ICUAS), 2017 International Conference on. IEEE, 2017, pp. 46–55.

[21] M. Chandarana, E. L. Meszaros, A. Trujillo, and B. Danette Allen, "Natural language based multimodal interface for uav mission planning," in Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 61, no. 1. SAGE Publications Sage CA: Los Angeles, CA, 2017, pp. 68–72.

[22] M. Chandarana, M. Lewis, K. Sycara, and S. Scherer, "Determining effective swarm sizes for multi-job type missions," in Intelligent Robots and Systems (IROS), 2018 IEEE/RSJ International Conference on. IEEE, 2018.

[23] S. Mehdi et al., "Bézier curves for safe cooperative atmospheric missions with multiple heterogeneous uas," in 16th AIAA Aviation Technology, Integration, and Operations Conference, 2016, p. 4229.

[24] B. N. Kelley, R. A. Williams, J. L. Holland, O. C. Schnarr, and B. D. Allen, "A persistent simulation environment for autonomous systems," in 2018 Aviation Technology, Integration, and Operations Conference, 2018, p. 4015.

[25] S. Jang, J. M. Vitale, R. W. Jyung, and J. B. Black, "Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment," Computers & Education, vol. 106, 2017, pp. 150–165.

[26] P. Walker, "Improving operator recognition and prediction of emergent swarm behaviors," Ph.D. dissertation, University of Pittsburgh, July 2017.

[27] M. Chandarana, M. Lewis, K. Sycara, and S. Scherer, "Decentralized method for sub-swarm deployment and rejoining," in Systems, Man, and Cybernetics (SMC), 2018 IEEE International Conference on. IEEE, 2018.

[28] B. D. Allen, "Serious gaming for building a basis of certification for trust and trustworthiness of autonomous systems," in 2018 Aviation Technology, Integration, and Operations Conference, 2018, p. 3844.

[29] E. L. Meszaros et al., "Evaluating communication modality for improved human/autonomous system teaming," in 2019 AIAA Science and Technology Forum and Exposition. AIAA, 2019.

[30] R. Banerji, "De-instrumentalizing hci: Social psychology, rapport formation, and interactions with artificial social agents," in New Directions in Third Wave Human-Computer Interaction: Volume 1-Technologies. Springer, 2018, pp. 43–66.

[31] Y. Candau, T. Schiphorst, and J. Françoise, "Designing from embodied knowing: Practice-based research at the intersection between embodied interaction and somatics," in New Directions in Third Wave Human-Computer Interaction: Volume 2-Methodologies. Springer, 2018, pp. 203–230.