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16. Abstract This project develops a novel gaze-directed UAV-UGV coordination framework for on-site quality inspection of precast bridge construction. UAV will provide global coverage for inspectors to quickly identify the components and construction activities for inspection while UGV will navigate to specific locations for close inspection following human guidance. A new gaze-directed human-machine interface, where inspectors can express their guidance via natural gaze movements, to reduce worker mental load. The framework is intended to transform the practice of onsite quality inspection for precast infrastructure construction by establishing intuitive multi-robot-human teaming for efficient inspection. Such a system can be extended to provide guidance during bridge installation, thus improving construction quality and durability with reduced rework. The researched framework can also be extended for lifecycle inspection, including offsite component inspection and condition monitoring of existing infrastructure, and eventually improve the durability and extend the life of precast transportation infrastructure.		
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Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Gaze-directed UAV-UGV Coordination Framework for Onsite Quality Inspection of Precast Bridge Construction
UT-23-RP-02

FINAL REPORT

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Executive Summary

Precast bridge components such as girders, decks, and columns facilitate accelerated bridge construction while offering improved construction quality. Onsite quality inspection for precast bridge construction is crucial due to potential defects after the offsite construction phase. For example, damage and defects may occur during the component transportation process. The quality of onsite construction activities such as connection joint sealing, post-poured wet joints, and component localization and alignment, also significantly affect the overall structural integrity and durability. Currently, quality inspection of precast components requires inspectors' visual check or data collection by carrying devices (e.g., 3D laser scanners) to different locations, which is very time-consuming, error-prone, and labor-intensive. There is a critical need to develop a robot-assisted platform to improve the efficiency and coverage of data collection and inspection for QA/QC of onsite precast bridge construction.

This project developed a novel gaze-directed UAV (Unmanned aerial vehicles) -UGV (Unmanned Ground Vehicle) coordination framework for on-site quality inspection of precast bridge construction. In the proposed framework, UAV provides global coverage for inspectors to quickly identify the components and construction activities for inspection while UGV navigates to specific locations for close inspection following human guidance. A new gaze-directed human-machine interface was developed, where inspectors can express their guidance via natural gaze movements to reduce worker mental load. A prototype was developed to integrate the entire framework, including a robotic hardware system for operation, deep learning models for data analysis, and a communication network for data transmission, along with a web-based user interface for intuitive implementation. The system was tested in both simulation and real-world controlled environments. The developed system offers a unified remote operator interface for gaze-based multirobot coordination. Through the use of intuitive gaze movements, our research project aims to reduce worker mental load, make inspection tasks accessible to a wider range of operators, allowing data to be rapidly captured and stored for documentation and verification purposes, and to increase single operator productivity by making remote operation more accessible and intuitive.

The proposed framework is expected to transform the practice of onsite quality inspection for precast infrastructure construction by establishing intuitive multi-robot-human teaming for efficient inspection. Such a system can be extended to provide guidance during bridge installation, thus improving construction quality and durability with reduced rework. The proposed framework can also be extended for lifecycle inspection, including offsite component inspection and condition monitoring of existing infrastructure, and eventually improve the durability and extend the life of precast transportation infrastructure.

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TRANS-IPIC Final Report:

1. Statement of Problem

Precast bridge components such as girders, decks, and columns facilitate accelerated bridge construction while offering improved construction quality due to the high quality control standards at the offsite precast plants. In the offsite precast plants, components need to go through rigorous dimensional and surface quality inspection, after which they are transported to the jobsite for final assembly [1]. Contrastively, onsite quality inspection, which still largely relies on manual visual inspection on limited samples, is yet to match up with the standards of the offsite practices [2]. Onsite quality inspection for precast bridge construction is crucial due to potential defects after the offsite construction phase. For example, damage and defects may occur during the component transportation process. The quality of onsite construction activities such as connection joint sealing, post-poured wet joints, and component localization and alignment, also significantly affect the overall structural integrity and durability. Recently, many sensing systems, such as laser scanning [3] and vision-based systems [4] have been developed for quality inspection of precast components. Most efforts have been dedicated to creating new data processing and analysis algorithms to improve accuracy, with very limited focus on improving the efficiency and accuracy of the data collection process using automated technology [1]. There is a critical need to develop a robot-assisted platform to improve the efficiency and coverage of data collection and inspection for QA/QC of onsite precast bridge construction. A reliable and efficient on-site quality inspection could ensure the long-term quality and durability of precast transportation infrastructure.

Currently, quality inspection of precast components requires inspectors' visual check or data collection by carrying devices (e.g., 3D laser scanners) to different locations [1], which is very time-consuming, error-prone, and labor-intensive. Unmanned aerial vehicles (UAVs) have enjoyed increased adoption in infrastructure inspection [5,6] given their advantages in rapid and large spatial coverage and the ability to reach inaccessible areas from the air. However, for UAVs alone, accessing ground activities is still difficult and unsafe when it is too close to work activities, coupled with limited payload. On the other hand, unmanned ground vehicles (UGVs) can carry larger payloads, hence better sensors, and operate for extended periods with better access to ground-level workspaces. However, UGVs usually have less field of view and lower coverage speed compared to UAVs [7]. Therefore, UAV-UGV coordinated systems are promising solutions with emerging applications in construction [7,8], space exploration and mapping [9], etc. Despite the great potential, ***two limitations*** persist for current UAV-UGV coordinated inspection. ***First***, UAV and UGV are often required to move in proximity for mutual localization. ***Second***, extensive human expertise and experience are still required, e.g., to determine the optimal route and/or find the optimal inspection location. Operators need to define waypoints prior to the mission, which cannot adapt to the dynamic work environment. In addition, the control of multiple robots typically relies on multiple controller devices, which may increase the human mental load and risk of error.

2. Research Objective, Tasks, and Results

2.1 Overall objective

The objective of this project is to develop a novel gaze-directed UAV-UGV coordination framework for on-site quality inspection of precast bridge construction. Our framework incorporates the unique strengths of aerial and ground robots in order to automate the inspection process. We proposed gaze as a primary interfacing means to broaden the accessibility of the interfacing system, allow operators to use their hands for other control interfaces such as mouse or keyboard, and reduce user mental workload on the operator. Figure 1 visually demonstrates a high-level visualization of this system. For this research project we broke down development into 3 key tasks.

- *Task 1. UAV-UGV coordinated localization and navigation.* This task aimed to develop a hierarchical framework that would enable a UGV to automatically locate and navigate to the inspection area as indicated by the UAV, leveraging sensing data from the onboard GPS and camera of both robots.
- *Task 2. Gaze-directed and AI-powered human-robot interface.* This task aimed to develop a gaze-directed and AI-powered human-robot interface (HRI) such that the robot could navigate to a specific location based on human gaze and gaze fixations.
- *Task 3. Prototype development and experimental demonstration.* This task involved the integration of the previous tasks and system evaluation in real-world settings.

For the remainder of this section, each task is detailed with its technical challenges and our developed solutions for robot-assisted onsite inspection.

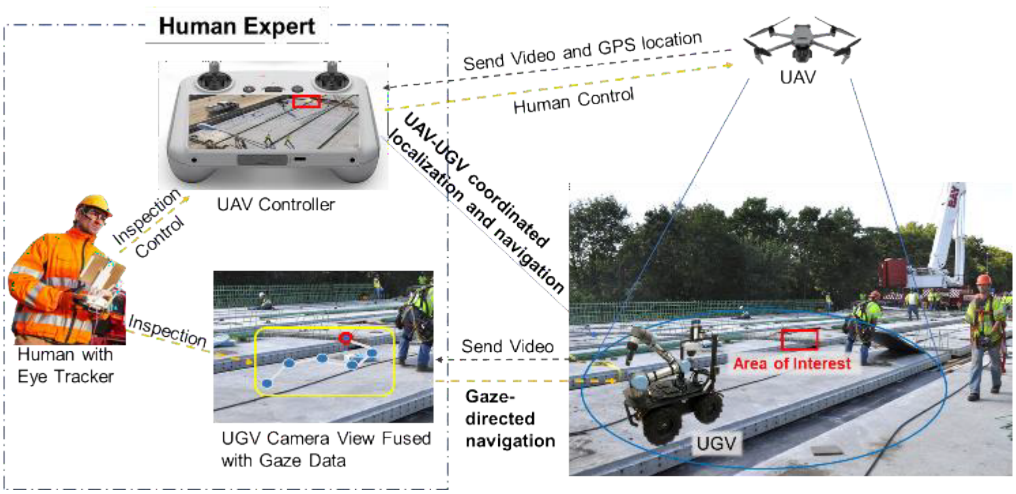


Figure 1. Gaze-directed UAV-UGV coordination framework for onsite quality inspection

2.2 Task 1. UAV-UGV coordinated localization and navigation

For outdoor environments, drones are generally able to cover more ground and have a wider operating space than ground-based mobile robots. However, drones tend to have shorter operation duration and lower payload capabilities due to the tradeoffs between payload and power requirements [10]. Ground robots have the capability of operating for longer duration due to increased payload capacity. For example, a Clearpath Husky A200 robot has a capacity up to 165 lbs and an operating range of 3-8 hours. Combining the two platforms would potentially allow for increased inspection coverage on a job site or even multiple sites by a single operator, leading to increased productivity. A common way of handling multi-robot coordinated navigation is through GPS-based navigation. Once a GPS point is reached by a ground robot, further methods are needed by the UGV in order to verify that it is in the correct location and to determine which target it should be inspecting.

We incorporate these ideas into our framework by allowing a drone operator to gather aerial reference image with a drone and then set GPS-based waypoints to the object which a UGV can then navigate to. The reference images capture the inspection target and any contextual details such as surrounding scenery or landmarks that can later be used for target identification by the ground robot. Figure 2 provides a system architecture of the GPS-based navigation and Figure 3 shows our simulated setup of this method in a Gazebo environment with a generic drone model and a simulated version of our lab's Clearpath Husky A200. The simulation demo video can be viewed in [this link].

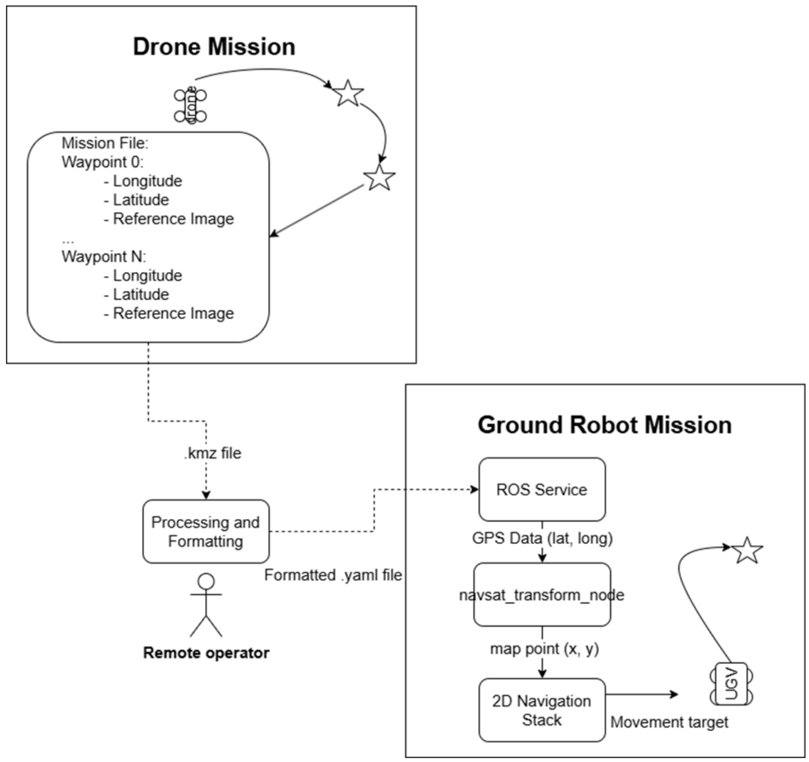


Figure 2. Visualization of multi-robot GPS waypoint creation and navigation.

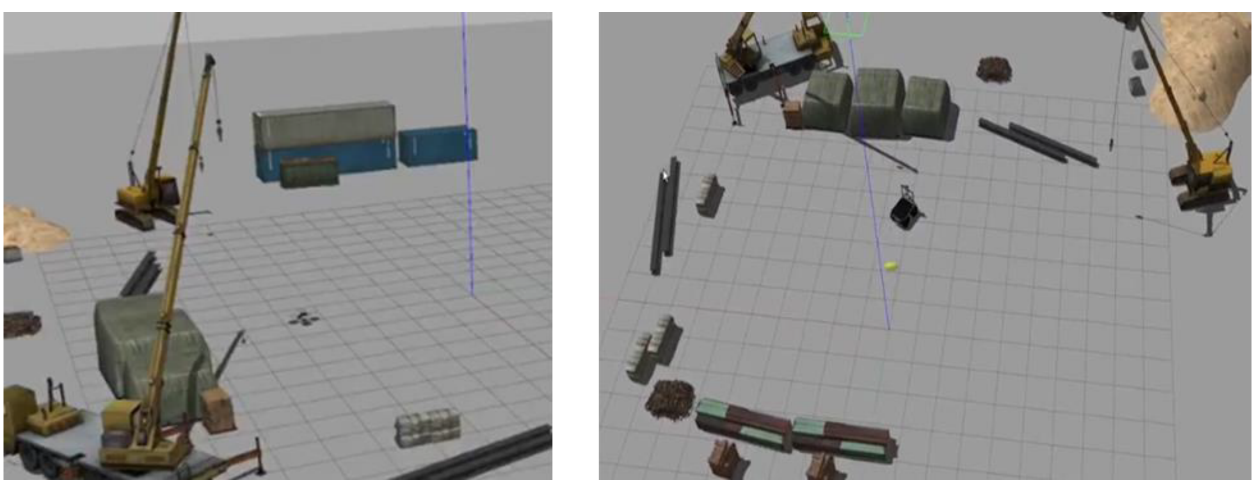
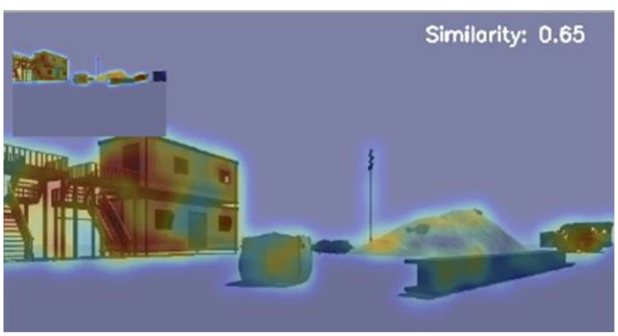


Figure 3. Drone and UGV in the Gazebo simulation environment.

Once the target point is reached, the UGV faces the challenging task of identifying the target in a scene. Construction sites are very dynamic with the interactions between equipment, materials, and workers so it is unlikely that the scene in a reference image captured by a drone would then completely correspond with the scene the ground robot finds at a later time. In addition, the perspective of the drone to the target object may not align with the perspective of the ground robot to the target, thus some homography transformation would be required to align the different perspectives.

For these two challenges we implement a recent visual correspondence model, XFeat [11], which uses a lightweight Convolutional Neural Network (CNN) architecture that achieves fast and accurate visual correspondence. XFeat showed top-of-the-line results on homography benchmarks for the HPatches dataset, in addition, the model architecture was shown to be faster than similar light weight matching methods while still being able to deliver a large amount of feature matches. The model achieves this lightweight and generalizable solution through their architecture which uses separate branches for keypoint detection and feature descriptor extraction. We incorporated the feature matcher into a software package and verified its functionality in a Gazebo simulation environment and on real world images. The software package was released under the MIT license here. We visually evaluated how the matcher handled different perspectives from different camera inputs. We used heatmaps to show feature point densities between a reference image and an image from a different perspective. The densest feature regions appear red then follow a color gradient down to the sparsest regions which appear blue. Sample visualizations are provided in Figure 4. The simulation demo of this matcher on the robot can be viewed here. A demo of the matcher on real-world data can be viewed here.



(a)

(b)

Figure 4. Feature matcher output rendering from an aerial reference image and a ground view perspective video. The top left image shows the aerial reference image while the center image is of the ground view. The top right-hand corner shows the similarity score result based on feature matcher outputs. (a) in simulation; (b) in real-world controlled environments

2.3 Task 2. Gaze-directed and AI-powered human-robot interface

For this task, we strove to create a way of capturing a skilled operator's gaze fixation on an inspection target and use that information to remotely direct a robot in an intuitive way. To accomplish this, we integrated promptable foundation segmentation models, SAM2 [12] and SAM [13], to perform zero-shot segmentation of targets of interests. This method allows any image pixel point (x, y) to be passed to the model along with the corresponding image in order to output multiple segmentation masks predictions. We can then use these masks to generate specific sections for a robot to inspect or discern one precast concrete member from another.

Our initial implementation consisted of an application using the pyQT framework for UI layout and the Pupil Labs Core gaze tracking glasses to capture a user's gaze. We streamed the video from a front-facing point-of-view (POV) camera on the Pupil Core glasses and associated fixations with the video stream. The fixation points would prompt a segmentation at the point location on to the latest video frame. When the segmentation is complete, the user would select 1 of 3 masks to send to the UGV. Figure 5 demonstrates the first implementation of the interface. The interface was included in a simplified test run where a user directed a ground robot to inspect a specific target with their gaze. After an operator fixated on a target and selected a segmentation mask of the target, the mask was transmitted to the ground robot so that the robot could match the mask to its current scene and then determine the distance of the matched object from the robot. This system is visualized in Figure 6. We show results from testing of the framework by a single operator in Table 1.

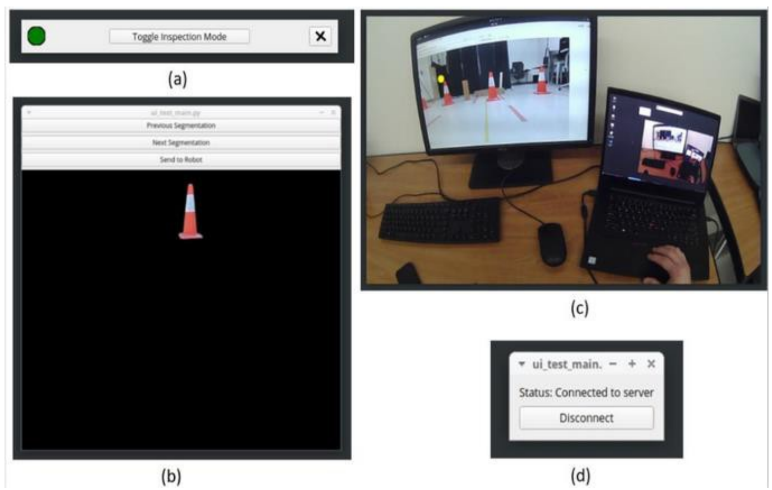


Figure 5. The original pyQT implementation of our user interface. This interface included separate floating tiles for the different comments of the application: (a) a Menu Bar, (b) a Segmentation Results window, (c) A video streaming window of the Pupil Core front facing world view camera, (d) a Network Status window.

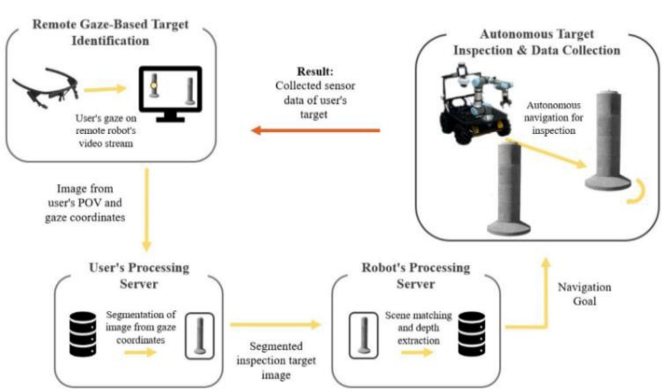


Figure 6. System diagram for initial gaze-based interface testing.

Table 1. Captured metrics from the experiment.

Object	Actual Distance (mm)	Program Output Distance (mm)	% Error of Distance Capture	Inspection Process Time (s)	Attempts to Acquire Target in Inspection Window	Scene Matching Process Time (s)
Large wood block	2742	2684	2.12 %	14.42	1	3.57
Small wood block	3068	3900	27.11 %	6.21	6	5.39
Cone	2440	2475	1.43%	7.36	2	2.68

Note: The “Cone” case reflects a false positive result from the feature matcher.

There were a few issues with this implementation. First, the image passed to the segmentation module was of a lower scale and different angle than the original image from the robot as we capture an output from the front facing camera of the Pupil glasses. To achieve a correspondence between the resulting mask and the robot’s actual image frame we implement a scale-invariant feature transform (SIFT) to match the features of the mask and the image frame. This has the potential of losing the operator’s original fixation target as an incorrect match could occur as noted in Table 1. We address these limitations in Task 3 with an updated interface and gaze-capturing technique.

2.4 Task 3. Prototype development and experimental demonstration.

The final task involved the integration of the previous two tasks into a unified framework. For this portion of the project, we moved the application to browser based and incorporated docker for the application building, which allowed us to quickly deploy the application on more devices and operating systems.

To address the possible loss of the intended target with the first interface implementation, we developed an improved system incorporating Apriltags [14]. The Apriltags allow for a direct transformation from gaze and fixation points in the world frame to a local bounded surface using the Pupil Capture software, the software enabling API interactions with the Pupil Labs Core gaze tracking glasses. We then added the digital AprilTag renderings within our application software, placing four tags at screen corners. This setup allows for direct correlation between gaze/fixation points to pixel coordinates from the UGV's video stream. Figure 7 illustrates this improved setup, showing how AprilTags create a bounded surface for gaze translation. The interface includes various convenience features for the operator including multi-camera streaming, real-time mission status monitoring, and dynamic gaze toggling. Gaze is rendered in real-time as green dots allowing the user to be able to tell when a calibration of the gaze tracking glasses is needed. Fixations are captured and rendered as a red dot on the corresponding image to be segmented. The system diagram in Figure 8 shows how the interface centralizes inputs from the drone and ground robot to facilitate the coordinated on-site inspection.

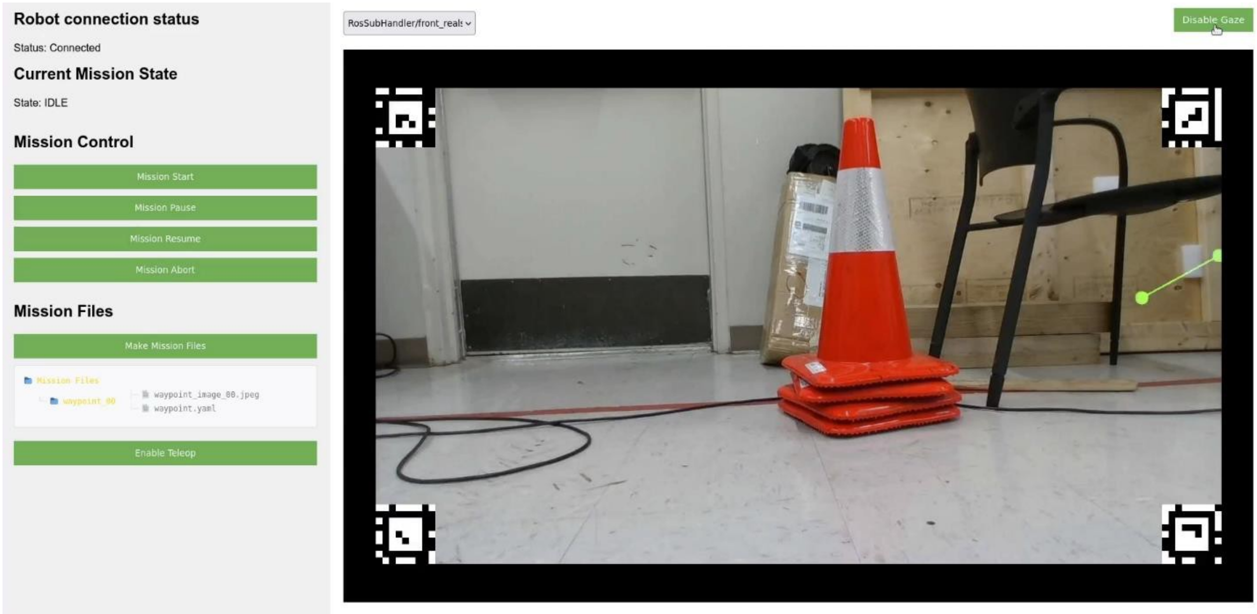


Figure 7. The latest user interface application including Apriltag rendering, gaze visualizations, multi-video input streaming, and mission-related controls and feedback.

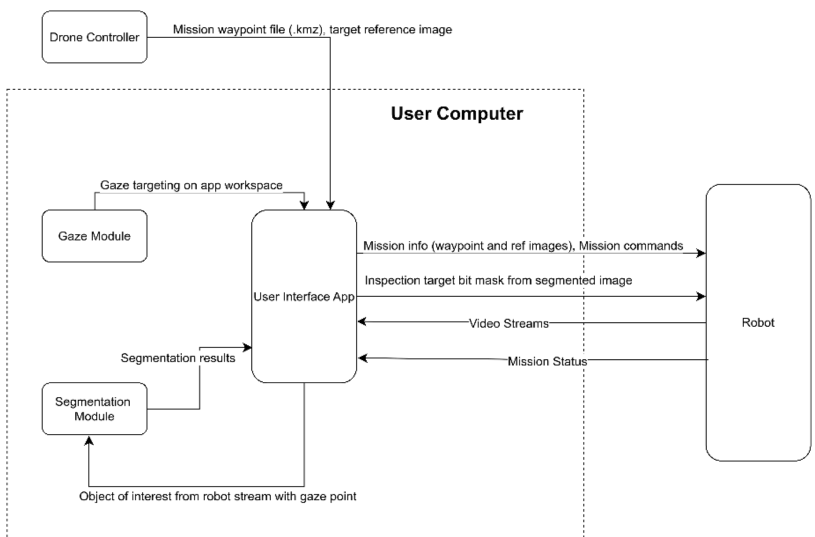


Figure 8. System diagram for multi-robot collaborative inspection mission.

To start an inspection mission, the operator pilots the drone to the inspection target, sets a GPS waypoint, and then captures images of the target. The data collected is uploaded from the drone controller to the operator's laptop and processed by the remote user application. From the application interface, the user then sends a "Mission Start" command to the ground robot. The ground robot converts the GPS coordinates into map point directions and creates a global and local navigation plan to autonomously navigate to the area. The operator monitors the robot's state and video feed for any issues or anomalies. When the target area is reached the robot scans its surroundings and uses the reference image and the feature matching network to orient itself so that it is facing the inspection target. The UGV then waits for a specific inspection area command from the operator. The operator at this point uses their gaze to look at the incoming video stream from the UGV and fixates on what part of the object the robot should inspect. The robot approaches the area and simulates an inspection. The inspection portion builds upon the developed gaze-to-segmentation-mask method developed in Task 2, where the operator fixates on a portion of the inspection target for the robot to thoroughly inspect. When the inspection is complete the operator could provide another inspection target or complete the inspection and move on to the next waypoint. If no more waypoints were available, then the mission would be completed. Figure 9 provides a visualization of the mission sequence. We released our code as open-source under the MIT license here.

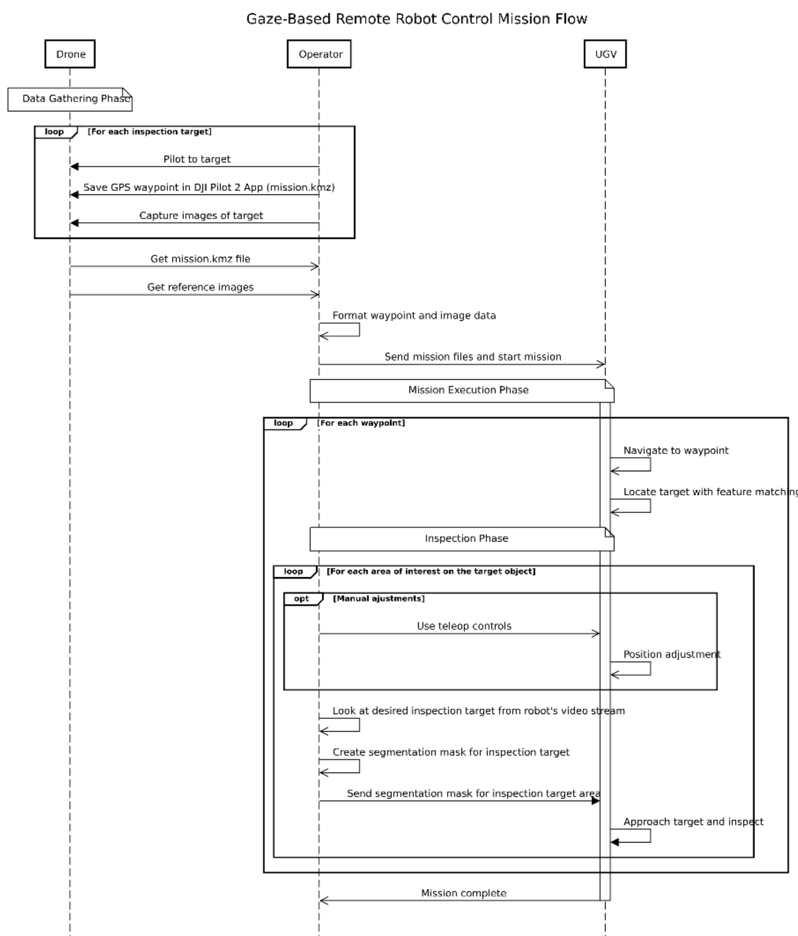


Figure 9. Sequence chart for multi-robot collaborative inspection mission.

The final prototype and experiment of our project involved field testing of our framework in an outdoor environment for the inspection of a target object. For this test we used a Clearpath A200 robot as the UGV and a DJI M30T as the drone. We conducted the final field testing in UTSA's drone enclosure area, a 15000 square foot and 60-foot-tall facility. An EAP225-Outdoor access point was set up to create a local wireless network between the ground robot and operator's laptop. A wooden mock bridge was set up inside of the drone cage to act as our inspection object along with construction cones to add noise to the environment. Figure 10 shows the setup and equipment for our outdoors test.

(a) (b) (c)

Figure 10. Images of the outdoor testing environment and inspection structure for the multi-robot collaborative inspection mission.

We did encounter issues with our navigation software where the robot would create paths into non-navigable locations and would create movement targets in the incorrect direction. The latter issue was addressed by updating the frame of reference used by the robot, however we could not resolve certain navigation issues in the field and are currently looking into the matter. Nonetheless we were able to test portions of the application and verify their functionality in a real-outdoor scenario. Figure 11 shows one of the results from a targeted fixation segmentation. We also compiled the testing results into an evaluation video found here.

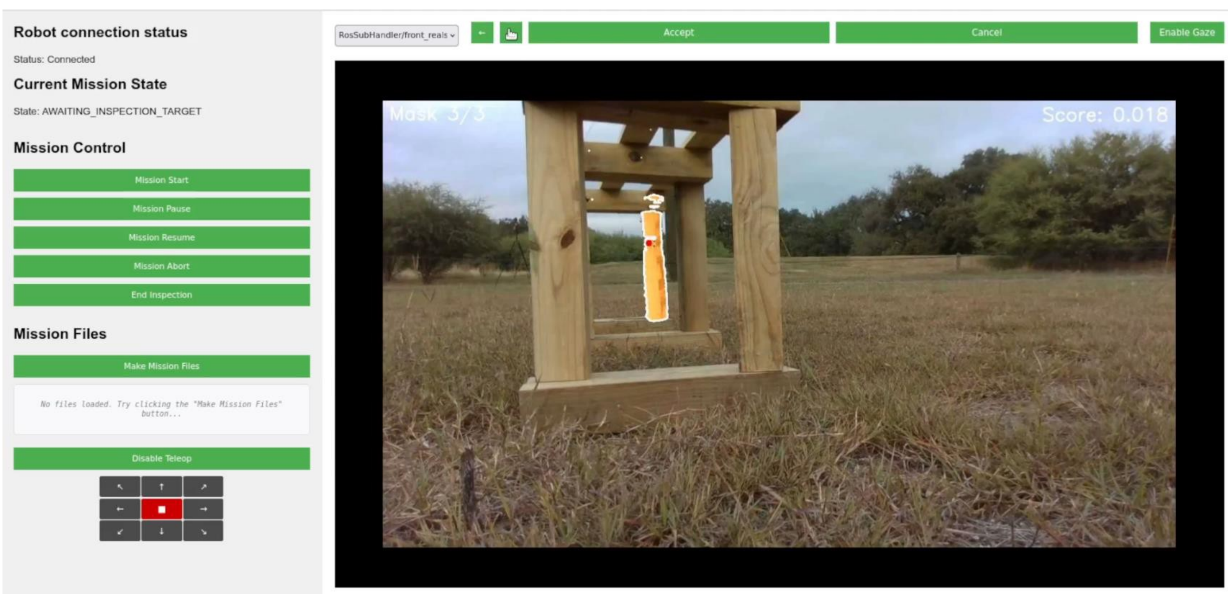


Figure 11. A segmentation mask visualization rendered in the latest user interface.

2.5 Conclusion and Future Work

During this research project we successfully developed a gaze-directed interface for UAV-UGV coordinated site inspection. Further testing is planned for the end of November and into December to gather user feedback on the completed system. A systems design paper is also being drafted. The initial work of this project has opened up a few potential research directions for enhancing the effectiveness of the system, such as incorporating cloud computing for running larger visual navigation models, improving the navigation to better handle dynamic and challenging environments found on real job sites, incorporating VR/AR technologies with our gaze-enable interface, and using the a robot manipulator to fully complete an inspection of a prefabricated component. In future study, we also plan to test the developed system in real-world transportation infrastructure project and improve the technology based on feedback from construction professionals.

3. Educational Outreach Activities

- *K-12 lab visit.* During the project period, we hosted around 10 K-12 students in the PI's lab for a half-day lab visit during the Summer 2024 period. During the visit we set up interactive games and hands-on activities designed to engage students in robotics, computer vision and AI concepts. Highlights of the event are shown in Figure 12.

Figure 12. Lab visit of K-12 students

- *High school student summer internship.* We also hosted a summer research internship program for high school students in Summer 2024. PI Cai mentored two high school students, with one student co-mentored by Co-PI Awolusi. The PI conducted weekly meetings with the interns while graduate students provided additional mentorship by designing mini projects which helped to contribute to the research efforts. This provided the high school students with direct exposure to research methods and laboratory equipment. The gaze-to-Apriltag-surface technology in Task 3 was partially developed during one of the internship mini-projects.

- *Graduate students training and mentorship.* Throughout the project, the research supported and trained four graduate students in robotics applications for transportation infrastructure: one master's student (Juan Cruz Rivera) and three Ph.D. students (Xiaoyun Liang, Mohsen Navazani, and Roy Lan). They were trained in conducting multidisciplinary research, and professional communication and academic writing. **Specifically, the master's student, Juan Cruz Rivers, who is the lead researcher on this project, was selected for 2024 UTC outstanding student award for his exceptional contribution and performance on this project.**

4. Papers of TRANS-IPIC UTC Funded Research

Two conference papers were accepted for publication for 2024 ASCE i3ce conference.

- Juan Cruz Rivera, Xiaoyun Liang, Ibukun Awolusi, Ao Du, and Jiannan Cai. (2024). A Gaze-Controlled Robotic Framework for Remote Site Inspection. ASCE International Conference on Computing in Civil Engineering 2024. (*in press*)

- Liang, X., Cruz Rivera, J., Cai, J., & Li, S. (2024). Gaze-enhanced and LLM-enabled System for Intuitive Human-Robot Collaboration. In *Computing in Civil Engineering* 2024 (*in press*)

5. Presentations of TRANS-IPIC Funded Research.

- Graduate student, Juan Cruz Rivera, presented at the 2024 ASCE International Conference on Computing in Civil Engineering a paper entitled, "A Gaze-Controlled Robotic Framework for Remote Site Inspection".
- Graduate student, Xiaoyun Liang, presented at the 2024 ASCE International Conference on Computing in Civil Engineering a paper entitled, "Gaze-enhanced and LLM-enabled System for Intuitive Human-Robot Collaboration".
- Graduate student, Juan Cruz Rivera, presented this project in the TRANS-IPIC monthly webinar.

6. News from Research

Our research with TRANS-IPIC was referenced in local news article covering UTSA's Drone cage facility.

References

[1] Z. Ma, Y. Liu, J. Li, Review on automated quality inspection of precast concrete components, Automation in Construction. 150 (2023). https://doi.org/10.1016/j.autcon.2023.104828.

[2] S.J. Leea, S.W. Kwon, M.K. Jeong, S.M. Hasan, A. Kim, Automated on-site quality inspection and reporting technology for off-site construction(osc)-based precast concrete members, in: Proceedings of the 37th International Symposium on Automation and Robotics in Construction, ISARC 2020: From Demonstration to Practical Use - To New Stage of Construction Robot, 2020: pp. 1152–1159. https://doi.org/10.22260/isarc2020/0158.

[3] J. Liu, Q. Zhang, J. Wu, Y. Zhao, Dimensional accuracy and structural performance assessment of spatial structure components using 3D laser scanning, Automation in Construction. 96 (2018) 324–336. https://doi.org/10.1016/j.autcon.2018.09.026.

[4] X. Luo, H. Long, S. Dong, J. Wu, Prefabricated Concrete Component Geometry Deviation Statistical Analysis, Mathematical Problems in Engineering. 2021 (2021). https://doi.org/10.1155/2021/9993451.

[5] J. Seo, L. Duque, J. Wacker, Drone-enabled bridge inspection methodology and application, Automation in Construction. 94 (2018) 112–126. https://doi.org/10.1016/j.autcon.2018.06.006.

[6] J. Seo, L. Duque, J.P. Wacker, Field Application of UAS-Based Bridge Inspection, Transportation Research Record. 2672 (2018) 72–81. https://doi.org/10.1177/0361198118780825.

[7] K. Asadi, A. Kalkunte Suresh, A. Ender, S. Gotad, S. Maniyar, S. Anand, M. Noghabaei, K. Han, E. Lobaton, T. Wu, An integrated UGV-UAV system for construction site data collection, Automation in Construction. 112 (2020). https://doi.org/10.1016/j.autcon.2019.103068.

[8] O. Elmakis, T. Shaked, A. Degani, Vision-Based UAV-UGV Collaboration for Autonomous Construction Site Preparation, IEEE Access. 10 (2022) 51209–51220.

https://doi.org/10.1109/ACCESS.2022.3170408.
[9] H. Qin, Z. Meng, W. Meng, X. Chen, H. Sun, F. Lin, M.H. Ang, Autonomous Exploration and Mapping System Using Heterogeneous UAVs and UGVs in GPS-Denied Environments, IEEE Transactions on Vehicular Technology. 68 (2019) 1339–1350. https://doi.org/10.1109/TVT.2018.2890416.
[10] R. Hadidi, B. Asgari, S. Jijina, A. Amyette, N. Shoghi, H. Kim, Quantifying the design-space tradeoffs in autonomous drones, in: International Conference on Architectural Support for Programming Languages and Operating Systems - ASPLOS, 2021: pp. 661–673. https://doi.org/10.1145/3445814.3446721.
[11] G. Potje, F. Cadar, A. Araujo, R. Martins, E.R. Nascimento, XFeat: Accelerated Features for Lightweight Image Matching, (2024). https://doi.org/10.1109/CVPR52733.2024.00259.
[12] N. Ravi, V. Gabeur, Y.-T. Hu, R. Hu, C. Ryali, T. Ma, H. Khedr, R. Rädle, C. Rolland, L. Gustafson, E. Mintun, J. Pan, K.V. Alwala, N. Carion, C.-Y. Wu, R. Girshick, P. Dollár, C. Feichtenhofer, SAM 2: Segment Anything in Images and Videos, (2024).
[13] A. Kirillov, E. Mintun, N. Ravi, H. Mao, C. Rolland, L. Gustafson, T. Xiao, S. Whitehead, A.C. Berg, W.-Y.Y. Lo, P. Dollár, R. Girshick, Segment Anything, in: Proceedings of the IEEE International Conference on Computer Vision, 2023: pp. 3992–4003. https://doi.org/10.1109/ICCV51070.2023.00371.
[14] J. Wang, E. Olson, AprilTag 2: Efficient and robust fiducial detection, in: IEEE International Conference on Intelligent Robots and Systems, 2016: pp. 4193–4198. https://doi.org/10.1109/IROS.2016.7759617.