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Human-in-the-Loop Teleoperation Modes for Autonomous Unmanned Aerial Vehicles

Kaya Kuru
School of Engineering and Computing
University of Central Lancashire
Preston, UK
https://orcid.org/0000-0002-4279-4166

***Abstract*—In all future scenarios of fully autonomous ground or air vehicle networks, human intervention is expected to take place in the form of remote immediate involvement/assistance. The use of telemanipulation with various "human-in-the-loop (HITL)" schemes is anticipated to instil the necessary degree of trust in autonomous vehicles (AVs) while operating in a highly volatile environment with other vehicles and a multitude of obstacles. According to numerous research papers, autonomous uninhabited aerial vehicles (A-UAVs) will reach higher penetration levels in mixed air traffic in the coming years. However, there hasn't been enough research in the literature on efficient A-UAV management in real-world use cases with a lot of uncertainty. This technical report attempts to bridge this gap by examining the telemanipulation schemes between two smart agents: human telemanipulators (HTMs) and A-UAVs. HITL telemanipulation described in this report can i) play a key role in enabling A-UAVs to instantly handle a multitude of uncertainties and ii) expedite the integration of A-UAVs into mixed air traffic.**

***Index Terms*—Telemanipulation, human–vehicle co-activity, human-vehicle teamwork, human-in-the-loop (HITL), autonomous unmanned aerial systems (UASs).**

I. Introduction

Research and commercial interest in autonomous unmanned aerial vehicles (A-UAVs), i.e. unmanned aerial systems (UASs), is growing exponentially in a diverse range of fields [1], [2], [3], [4], [5] is driving the development of autonomous flying robots [6], [7], [8]. [9] examined 10 levels of controlling UAVs, ranging from fully controlled level to fully autonomous level. Based on degrees of independence, Drone Industry Insights (DRONEII) classifies UAV autonomy into five levels [10], 1: low automation (i.e. at least one essential task is under the control of the UAV, piloted by a human); 2: partial automation (i.e. under certain circumstances, the UAV can take over bearing with altitude changes, with the pilot still in charge of ensuring the accomplishment of task safely); 3: conditional automation (i.e. all tasks can be completed by the UAV, and a pilot serves as a backup plan); 4: high automation (i.e. because of its backup systems, the UAV can continue to function even if a pilot is not present); 5: full automation (i.e. the UAV can use cutting-edge Artificial Intelligence (AI) autonomous learning techniques to plan its actions) with minimal to no involvement from humans in the control loop. UAVs can perform more complex tasks and function in more intricate environments with less operator interaction and less prior knowledge as their level of autonomy rises [11]. As a result of taking on more and more tasks that require decision-making skills, vehicles are becoming more and more automated. This is due to intelligent control systems that are getting better with advanced sensors and actuators using AI [12]. The ultimate goal of these systems is full autonomy [13]. When given an autonomous task, fully human-out-of-the-loop autonomous systems are expected to decide on their own what to do [14] with their advancing automation-in-the-loop (AITL) abilities. Nevertheless, fully autonomous vehicles (AVs) in the future are anticipated to involve human intervention in the form of a remote supervisory role [15]. A-UAVs are expected to be integrated into mixed aerial traffic readily thanks to location-independent remote real-time human-in-the-loop (HITL) approaches that use human telemanipulators (HTMs) skills in a supervisory role. "In-vehicle teleoperator" and "human telemanipulator" are referred to as "A-UAV or or AITL agent" and "HTM or HITL agent" respectively in this report. Remote involvement of human telemanipulation expertise, just in case, would increase the confidence of the general public, involving all stakeholders, in A-UAVs [16]. There are still many limitations with AVs despite several decades of earlier research and a renewed focus from the scientific community and major technology companies, which is what makes the HITL concept a reasonable remote involvement in managing AVs [17]. With the use of cyber-worlds implanted in the real world, or digital twins (DTs) [18], we can now teleoperate distant objects thanks to recent advancements in cyber-physical systems (CPSs) within the aspects of Automation of Everything (AoE) and Internet of Everything (IoE) [19], [20], [21].

When the new operator – an AI agent – experiences an unusual adverse condition that the autonomous capabilities are unable to handle, HITL telemanipulation, which extends

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human sensing and control capabilities, can aid in overcoming difficult tasks [22]. DTs facilitate the mapping of physical assets' dynamic real-time properties into the counterpart cyber-world in multidimensional space [23], [24], [25], [26], [27]. HTMs can monitor, communicate with, and modify the states of remote aerial robotic vehicles appropriately thanks to DTs of aerial traffic [28]. The report in [29] explored the telemanipulation schemes with ground-based self-driving vehicles (SDVs). The real-world AV ecosystem and the cyber-world mirroring of this ecosystem, i.e. augmented DTs of aerial traffic, are two analogous remote environments. A human telemanipulator (HTM), as a biological agent, can be immersed through these DTs to co-work with A-UAVs [30]. In the context of human-vehicle teamwork, this technical report examines the real-time remote human involvement with various HITL delay-sensitive telemanipulation schemes with A-UAVs.

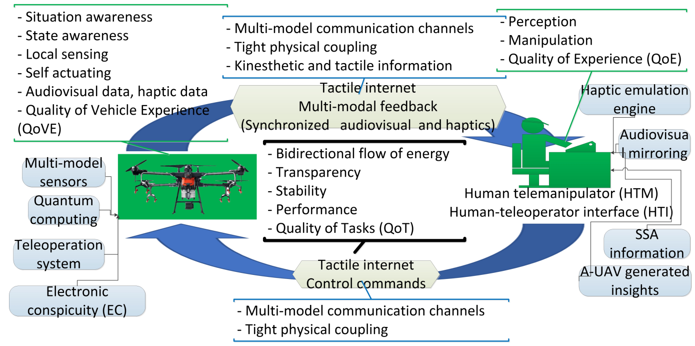

Fig. 1: Components of human haptic close-loop telemanipulation of A-UAVs with complete situation awareness using electronic conspicuity (EC).

II. Telemanipulation Schemes with A-UAVs

The way automation interacts with humans has started to shift significantly as it has become more advanced, going beyond what is typical for the humans-are-better-at/machines-are-better-at (HABA/MABA) paradigm, in which machines and humans compete with one another to seize the other's work [31]. The human-agent-robot teamwork (HART) framework enables humans to co-work with machines to create profitable applications by utilising their complementary strengths [32]. This report examines the co-work from the viewpoints of two smart, self-sufficient entities – a HTM and an A-UAV – that are highly reliant on one another to successfully manage uncommon challenges remotely using the HART-centric principles. The telemanipulation schemes should take into account the cognitive intelligence of HTMs and the self-deterministic autonomous capabilities of A-UAVs to make decisions for themselves where time-varying delays are an inevitable part of teleoperation.

A-UAVs operate autonomously and need to receive assistance whenever necessary. Sole human teleoperation without using local vehicle intelligence is dependent on motor skills, spatial orientation abilities and perceptual and cognitive capacities of HTMs to avoid risky adverse conditions, even with an intact SSA [14]. To this end, it is important to use the intelligence at the remote site and it is advantageous to co-work during the execution of complex tasks that cannot be handled by autonomy. If A-UAVs are capable of performing on their own, human intervention is not needed, allowing human-on-the-loop (HOTL) systems by which HTMs are not required to monitor the system. The HOTL system can turn into the HITL monitoring system when assistance requests are triggered by A-UAVs. A remote extension of human intelligence and expertise with HITL interaction may be necessary either for better task performance to avoid disastrous situations during possibly hazardous operations or for executing very complex tasks beyond the capabilities of autonomy. HTMs with the HOTL interaction scheme can change the state to HITL to monitor the aerial traffic at any time and take action in one of the telemanipulation schemes to ascertain aerial safety or to accomplish any particular tasks. Then, the HITL state can be switched to the HOTL state after any uncertainty is managed successfully.

A tight communication channel with high bandwidth capabilities (i.e., ultra-reliable and low-latency communication (URLLC)) between two nodes is one of the key components of basic haptic communication between HTMs and A-UAVs, as illustrated in Fig. 1. Other components include a haptic engine and DTs of aerial traffic using electronic conspicuity (EC) (ADS-B, Sky Echo, PilotAware, Mode-S with Weather RADAR and Enhanced Traffic Data) for aerial traffic and a multitude of sensors and actuators, in particular, for object avoidance. These elements are necessary to address the challenges in telemanipulation. With the right haptic rendering capabilities, the haptic emulation engine enables HTMs to control and sense A-UAVs in intricate aerial environments. The major goal of utilising those components in remote operations is to assist HTMs in experiencing and perceiving a realistic SSA of A-UAVs, enabling them to make timely and appropriate decisions for safely supervising A-UAVs while maximising their task performances [33]. By enabling near-real-time bidirectional mirroring between two entities, transparent DTs of aerial traffic assist HTMs in tightly coupling themselves in telemanipulation over the URLLC channel. To establish a task optimally, two smart nodes need to formulate how to co-work in an anticipated manner. When an A-UAV encounters a confusing scenario, it initiates a telemanipulation scheme by sending a teamwork request to a HTM. The HTM may: i) not need to seize control; ii) partially take control when the AV anticipates the HTM's operations in the context of human-vehicle shared control and help to accomplish the desired task smoothly; iii) take control when the automation-in-the-loop (AITL) agent may not necessarily relinquish the actuation triggered by the HTM in the context of human-vehicle joint control; or iv) fully take control of all AV operations. Fig. 2 shows these HITL telemanipulation schemes as "No-control (fully supervisory)", "co-activity (shared)", "collaboration (joint)", "full control (master-slave)", and "cooperation (all togetherness)". By utilising intelligence at the site of A-UAVs and the cognitive capacity of humans, these schemes aim to define roles, responsibilities, and courses of action in the event of a co-activity conflict between two smart nodes. The following sub-sections are dedicated to summarising those schemes.

A. No-Control (Supervisory) Scheme (Fig. 2 A)

This is a time when AI's superiority over humans can be demonstrated empirically to such an extent that human direct operational inputs could have a negative impact on task performance. The involvement of HTMs is aimed to be minimised in this scheme. As a task-specific HITL, the HTM encourages the indecisive A-UAV to choose between options determined by the HTM or those determined by the vehicle itself. The HTM assists A-UAVs by both setting short-range sub-goals/subtasks for the AITL agent to achieve independently to reach the final goal and giving A-UAVs a high degree of freedom. A complex task (e.g. collision avoidance) can be divided into a sequence of subtasks (e.g. increase altitude, change heading +20, land) that the AITL agent can achieve on its own. This can be executed using simple commands that can be readily generated through the user interface. The commands may be "YES", "NO", "OPTION:1", "HEADING:-15" or "ALTITUDE: +30". Additionally, the HTM may continue his/her supervisory duties during the execution of a task by the A-UAV. Considering the parameters of the task concerning SSA, any instantaneous suggested trajectories dictated by informative waypoints can be instructed to help the A-UAV navigate properly to handle challenging predicaments encountered. As the other side of the teamwork, the HTM may keep an eye on the A-UAV as a HITL agent while the recommended course of operation is carried out without the need for direct human intervention. In this capacity, the HTM will stay in the supervisory role but be constantly alert for new instructions or take over the vehicle in the event that the implementation or navigation is not to the HTM's satisfaction. The HTM may choose to switch from the HITL state to the HOTL state after the guidance is conveyed to the vehicle without monitoring the actions taken by the A-UAV. This decision is strictly dependent on the capability of autonomy and the complexity of the task. Through autonomy's highly adaptive conceiving process, the implemented course of action is learned to be followed in a similar situation the next time without informing the HTM. This scheme is preferable under poor communication circumstances and may be ideal for non-experts in direct telemanipulation. The AITL agent seeks advice for an unorthodox situation and the HTM comes up with a response that allows the AITL agent to act on its own using provided advice. The AITL agent, while seeking dialogue, can still perform with the best option determined by itself even with no response from the HTM. This frees the HTM from interfacing with the AITL interaction scheme. It must be pointed out that the no-control scheme is also one of the intervention dialogues between A-UAV and HTM agents.

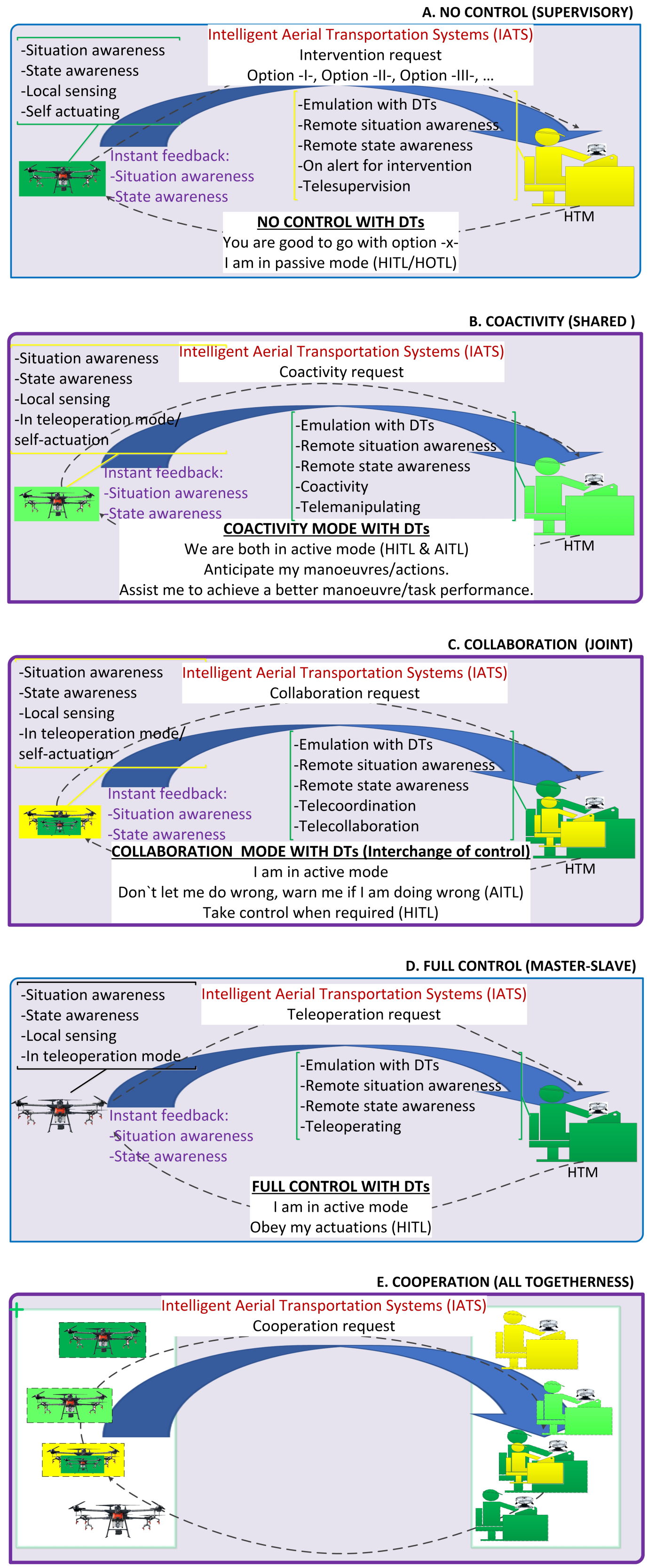

Fig. 2: HITL telemanipulation Schemes: "No-control (supervisory)", "co-activity (shared)", "collaboration (joint)", "full control (master-slave)", and "cooperation (all togetherness)".

B. Co-activity (Shared-Control) Scheme (Fig. 2 B)

It's possible that some tasks cannot be achieved as desired by distributing subtasks between HTMs and A-UAVs, which may lead to compromising task performance. Thus, a major objective of robotics is to find co-activity ways to seamlessly combine human and robot control so that the combined system can outperform both with less effort from the human side where it seems very appealing to combine human and robot skills via intelligent interfaces [34]. A simultaneous synergistic tighter one-to-one or one-to-many co-activity, i.e. master-master (i.e. more equal co-worker), needs to be built within a simultaneous, reciprocal interaction with mutual trust and shared effort to complete the task satisfactorily. The notion of "shared autonomy" stems from the combination of human operator inputs and autonomous system computation to generate the desired robot behaviour and it usually becomes helpful when there are noticeable communication delays [35]. This scheme assists both intelligent agents – HITL HTM and AITL AI – in achieving the common goal safely. Furthermore, given the shifting human psychological selective perception influenced by mental/psychological state, attention span, Quality of Experience (QoE), traits, attention span, fatigue, and dynamic environmental factors, the HTM might not be able to replicate the exact manoeuvres of the A-UAV when completing the same task again. The manipulation may occasionally be similar with similar manoeuvres but, not the same, resulting in the accomplishment of the task with varying Quality of Task (QoT) parameters/performances. It may occasionally lead to complete failure, such as when it causes fatal accidents. The QoT can be significantly impacted by volatile QoE, and it might be difficult to quantise a vehicle teleoperation system using the predetermined performance metrics. To address similar disparities in the system, the co-activity scheme places no full control of the A-UAV on the HTM, nor does the A-UAV have full control over itself; rather, they tightly co-work to successfully complete challenging tasks or crucial exceptional manoeuvres. Knowing the primary objective (ascertained by the HTM or by the A-UAV itself), the A-UAV anticipates the HTM's upcoming manoeuvres and helps him/her proactively to carry them out smoothly and efficiently to improve outcomes. The AITL agent can appropriately and slightly deviate from the HTM-specified trajectory to avoid any adverse condition, e.g. collision avoidance with an object or skipping an obstacle, without notifying the HTM. This scheme aims to perform tasks in a synergistic manner by applying a socio-cognitive model to accomplish them safely and effectively. The built-in safety features of vehicles, such as collision avoidance, always function (Fig. I). In this scheme, full co-activity between HTMs and A-UAVs aims to address the current challenge encountered or complete a task of superior quality. The commands of HTMs may be overridden by autonomy and vice versa to avoid serious results, in particular, in possibly dangerous environments as expressed earlier. To summarise, roles and responsibilities may not be distinctively assigned in this scheme, they are rather co-activated. In other words, differences between the commands of AITL and HITL agents may be slightly or significantly different from each other for a specific task and these commands need to be moulded to meet an agreed-upon efficient satisfactory task implementation. The final vehicle implementation input is the fusion of the HTM and AITL agents' task-oriented manipulation/modification/calibration inputs in the human plane and the A-UAV plane. The tight coupling of the HITL and AITL planes is expected to yield substantial improvements in overall performance that cannot be achieved individually.

C. Collaboration (Joint or Traded Control) Scheme (Fig. 2 C)

A series of assigned or distributed fine-granular sub-tasks need to be performed individually either by the AITL agent or HITL agent. HTMs do not have complete control over A-UAVs, and A-UAVs do not have complete control over themselves where these sub-tasks are traded back and forth between them to enable joint problem-solving. Partial control can be mainly used for tightly coupled coordination between collocated HTMs and A-UAVs to achieve joint task performance wherever difficulty that cannot be coped with by the autonomy is alerted. Humans and robots converge to exchange ideas and settle disagreements rather than a superior giving orders to a subordinate [36]. The collaborative scheme was explained by Fond et al. [36] as "an important consequence of collaborative control is that the robot can decide how to use human advice: to follow it when available; to modify it when inappropriate. This is not to say that the robot becomes a "master": it still follows a higher-level strategy set by the human. However, with collaborative control, the robot has more freedom in execution. As a result, teleoperation is more robust and better able to accommodate varying levels of autonomy and interaction." It is important to note that in a highly complex urban mixed traffic setting, it may be impossible to anticipate all forthcoming circumstances (such as subtasks) when completing a task. In such conditions, HTMs steer A-UAVs and choose to take charge temporarily to improve task performance. In contrast to the no-control scheme, this time AITL agents are fully prepared to get involved by utilising their local advantageous SSA capacity, where the A-UAVs' built-in safety features (collision resolution) are always in operation (Fig. I) to prevent any hazards.

If the HTM's actions are deemed inappropriate (e.g. collision detection) by the A-UAV on the basis of local SSA information, the AITL agent, with a degree of autonomy, might not adhere to the HTM's actions. The AITL agent may need to generate an alternative course of action. This non-compliant behaviour with an explanation (e.g. probable collision!!! I need to modify my heading and altitude) is sent to the HTM. The HTM may i) respond to the request in another way or ii) let the A-UAV fully control itself or iii) be adamant about his course of action. The A-UAV comply to perform the dictated course of actions if it is insisted by the HTM where the HTM is accountable for any possible adverse outcomes. For tasks that need to be completed by the vehicle, the HTM returns control to the AITL agent. The HTM can give the A-UAV

TABLE I: Main properties of the telemanipulation schemes.

Schemes	Loop	Decision	Obedience A-UAV	Obedience HTM	Solution for conflicts	Full control	Built-in safety
No-control	HITL	HTM	Yes	No	N/A	Yes (A-UAV)	Operational
Co-activity	HITL & AITL	HTM & A-UAV	No	Yes	HTM & A-UAV	No	Operational
Collaboration	HITL || AITL	HTM || A–UAV	No	No	HTM || A-UAVs	Partial	Operational
Full-control	HITL	HTM	Yes	No	N/A	Yes (HTM)	Inactive
Cooperation	Mix interactions	Mix schemes (above)	Mix schemes (Yes||No)	Mix schemes (Yes||No)	Mix schemes (above)	Mix schemes(above)	Operational

TABLE II: Transitional responsibilities between the telemanipulation schemes.

Switching between schemes	Current control	Next control	Current dominance	Next dominance	Switching control
No >>>>co-activity	A-UAV	A-UAV-HTM	A-UAV	A-UAV&HTM	A-UAV
No >>>>collaboration	A-UAV	A-UAV-HTM	A-UAV	HTM	A-UAV&HTM
No >>>>full	A-UAV	A-UAV-HTM	A-UAV	HTM	A-UAV&HTM
co-activity >>>>collaboration	A-UAV-HTM	A-UAV-HTM	A-UAV&HTM	HTM	HTM
co-activity >>>>full	A-UAV-HTM	A-UAV-HTM	A-UAV&HTM	HTM	HTM
co-activity >>>>no	A-UAV-HTM	A-UAV	A-UAV&HTM	A-UAV	A-UAV
Collaboration >>>>full	A-UAV-HTM	A-UAV-HTM	HTM	HTM	HTM
Collaboration >>>>no	A-UAV-HTM	A-UAV	HTM	A-UAV	HTM&A-UAV
Collaboration >>>>co-activity	A-UAV-HTM	A-UAV-HTM	HTM	A-UAV&HTM	HTM
Full >>>>no	A-UAV-HTM	A-UAV	HTM	A-UAV	HTM&A-UAV
Full >>>>co-activity	A-UAV-HTM	A-UAV-HTM	HTM	A-UAV&HTM	HTM
Full >>>>collaboration	A-UAV-HTM	A-UAV-HTM	HTM	HTM	HTM

control to complete any instantaneously emerging subtasks. The HTM, as a sub-task-specific HITL agent, is constantly ready to take over when the A-UAV is carrying out the subtasks that have been assigned to it. The collaboration is conducted under the HTM's supervision (Fig. I). However, the AITL agent may override the HTM when there is a hazardous situation based on the onboard intelligence that uses the local SSA. In other words, the control inputs from the HTM are implemented if they are determined to be safe by the AITL agent; otherwise, the control inputs of the AITL agent are implemented. Collaborative control helps balance the roles of HITL and AITL agents, giving the AITL agent more freedom in execution and allowing it to better function if the operator is inattentive or making errors [36]. This scheme seeks to accomplish a task more effectively than either a human or an A-UAV working alone.

D. *Full-control (Master-Slave) Scheme (Fig. 2 D)*

Complete tasks may need to be performed by HTMs alone under extreme conditions in this scheme. HTMs, as leading agents, take over the control and lead A-UAVs as follower agents. Different from the collaboration scheme, A-UAVs, piloted remotely by HTMs, comply with HTMs' manoeuvres under all conditions. This scheme does not take advantage of A-UAVs' local intelligence, which requires significant and careful assistance from HTMs. HTMs complete tasks/subtasks using fully human-controlled teleoperation. This scheme may be chosen in one of two ways: either i) due to a number of critical onboard sensor failures that compromise the SSA and/or failures of primary actuators needed for critical manoeuvres, or ii) due to some further global SSA information that A-UAVs are not able to access, but that is available to A-UAVs. To summarise, teleoperation with this scheme is performed with the direct HTM control of A-UAVs when they must be remotely controlled if they are not able to operate under their autonomous scheme due to any failure in their whole system, any subsystem or the difficulty level of tasks/sub-tasks that cannot be achieved by the autonomy requiring a complete HTM involvement. Landing the vehicle safely might be a strong option for the HTM.

E. *Cooperation (All Togetherness) Scheme (Fig. 2 E)*

Swarms of A-UAVs sometimes need to interact with each other to accomplish a specific task faster than a single A-UAV or to solve difficult tasks that are beyond a single A-UAV's capability where each A-UAV assists in the accomplishment of the desired goal considering its specific capabilities, e.g. deploying several A-UAVs for search and rescue missions, each with a distinct targeted Region of Interest (RoI), or transporting a hefty payload. In this scheme, the scope of the assigned task of an A-UAV is strictly related to the scope of other assigned tasks to the other A-UAVs leading to the accomplishment of a common goal as a teamwork. The number of A-UAV agents in the established cooperation environment may change during the execution of tasks. New A-UAV agents may be added to the cooperation and the A-UAV agents in the already established cooperation environment may leave while individual subtasks are being executed. In these situations, a single HTM or multiple HTMs can assist in achieving the task successfully through telecoordination with the established mutual trust between A-UAVs and HTMs. Cooperation of multiple A-UAVs and HTMs through the use of multiple telemanipulation schemes with high dimensionality requires a level of high dynamic goal-seeking coordination from the perspective of one-to-many or many-to-many human-robot systems. This scheme aims to ensure the harmonic manoeuvring of A-UAVs. The cooperation scheme is the use of at least two of the other 4 schemes at a time by incorporating more than one A-UAV and more HTMs if required to accomplish a complex task (beyond the capability of a single A-UAV or a single HTM) altogether.

III. Evaluation of the Telemanipulation Schemes

Table I summarises the primary distinguishing characteristics of the telemanipulation schemes. Combining these telemanipulation techniques as displayed in the scheme of "cooperation (all togetherness)" (Fig. 2) can be used to overcome extremely challenging tasks by alternating between schemes for certain portions of a complex task. The primary issues in such situations may be how and when to implement switching to another scheme (and switching back as well), particularly in the case of a high-speed vehicle. As previously stated, A-UAVs, with immediate SSA, may have a distinct advantage if they take the initiative to decide how the switching decisions would be implemented. However, the transitional responsibilities with schemes between two intelligent nodes have to be designated based on the instant dominant position and characteristics of the schemes as summarised in Table II. As an illustration, the transitional order from "No-control (fully supervisory)" to "co-activity (shared)" and then to "collaboration (traded)" and then to "full control (master-slave)" and then back to the starting scheme, "no-control (fully supervisory)", is executed by A-UAV, HTM, HTM and 'HTM & A-UAV together' respectively.

IV. Discussion and Conclusion

The "everyday things" in our environment have been getting more intelligent in recent years thanks to CPSs and improved AI techniques, allowing them to make decisions for themselves with a growing degree of autonomy with little to no assistance from humans [37]. The audacious goal is for all vehicles to be controlled centrally by 2040 [38]. Consequently, it is important to include remote problem-solving capabilities in the design and development stages of A-UAVs. In such situations where the new operator – an AITL AI agent – is unsure of how to operate while completing a task, remote telemanipulation allows an experienced HTM to co-work with an A-UAV remotely. Maintaining trust in A-UAVs can be achieved through HITL telemanipulation until A-UAVs become completely self-sufficient. This paper discusses the teamwork of humans and autonomous aerial vehicles in delay-sensitive HITL telemanipulation schemes. This is the first comprehensive report that, to the best of the observed knowledge, aims at closing a literature gap in HITL telemanipulation with A-UAVs. An extensive discussion of telemanipulation schemes and how to create the best possible location-independent co-work between intelligent A-UAVs and skilled HTMs is given in this report. By enabling remote presence, HITL telemanipulation with the critical, economical, and timely involvements described in this report can play a key role in enabling A-UAVs to instantly handle a multitude of uncertainties. A platform was designed to test and evaluate the above-mentioned telemanipulation schemes in [39], [40], [41], [42], [43] by the author of this paper. The future objective is to investigate the training of drones with RL (e.g. Transfer Learning (TL)) [44], [45] and Federated Learning (FL) [46], [47] using the gained experience during the manipulation of A-UAVs by HTMs, which will help A-UAVs to gain further autonomy to operate independently after learning what to do under uncertainties.

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