Editor’s comments

We have received the reports from our advisors on your manuscript, 'Robot Movement Based Inference of Teleoperator State for Multi-robot Search', which you submitted to Complex & Intelligent Systems.

Based on the advice received, I have decided that your manuscript could be reconsidered for publication should you be prepared to incorporate major revisions. When preparing your revised manuscript, you are asked to carefully consider the reviewer comments which can be found below, and submit a list of responses to the comments. You are kindly requested to also check the website for possible reviewer attachment(s).

Also, please avoid superfluous citations from "Complex & Intelligent Systems" publications. Only those papers that materially support or extend discussions of your work should be cited.

Thank you for handling our submission. We are grateful for the time and feedback from the experts. We have addressed all Reviewer comments below.

Reviewer #1: The manuscript investigates how a teleoperator's movement patterns during UAV control can reveal information about their prior knowledge, cognitive load, and situational awareness during search and rescue operations.  
The following issues need to be considered:

1. The authors note that situational awareness showed only weak correlations with movement behaviors. Could the authors elaborate on whether these correlations might be stronger in high-stress environments compared to your controlled experimental setting?

Thank you for the comment, yes you are right. We have addressed this point by updating our discussion, especially section 8.3 paragraph 2.

“…. emerged as the more reliable indicator. Under stressful conditions, tele-operators may display more exaggerated movement patterns (such as increased speed or sharper turns) and amplified physiological responses, which could enhance the detectability of SA-related cues. Although this investigation specifically examined Level 1 SA (environmental perception) in a controlled virtual setting, elevated stress levels might impair higher-order SA (environmental comprehension and predictive capability), potentially making movement-based inferences more robust in real-world operational scenarios.”

1. Your research indicates that adaptive search based on movement cues outperforms random search but has lower success times than spiral search. What specific operational contexts might favor the adaptive approach despite this time difference?

Thank you for the comment. In general we report that the adaptive search success rates are somewhat lower than the spiral search success rates ( spiral search finds the missing person 100% of the time), however we also report that the time to find for adaptive search is lower and thus better than any spiral search time to find. To make it clear we have added the following paragraph in section 8.4.

**Comparison of Spiral Search and Adaptive search methods**

The simulation results highlight that the choice between adaptive and spiral search strategies should be made on mission priorities. While spiral search achieves near-perfect success rates (consistently finding the missing person in virtually 100% of cases), adaptive search strategies exhibit slightly lower success rates. However, the advantage of adaptive search strategies are in operational efficiency, i.e. it significantly outperforms spiral search in terms of time to find across all tested conditions and swarm sizes. This reduction in search duration is substantial, often exceeding 150 seconds in scenarios involving larger swarms (15 robots) with both prior knowledge available to teleoperator, and about 100 seconds when no prior knowledge is available. Spiral search offers higher reliability at the cost of higher time to find.

1. The manuscript mentions that cognitive load measures showed unexpectedly weak correlations with movement. Have the authors considered whether the relationship might be non-linear or threshold-based rather than continuously correlated?



For the turn rate I think that there is some 2nd order relationship with the cognitive load

1. Your experimental design used a virtual replica of the Grand Canyon. How confident are the authors that the findings would generalize to different terrains with varying visibility conditions and topographical features?

Thank you for the comment, we believe that different topology will not affect the initial search performance however low visibility can extend search time and number of false positives. We added the following section under discussions.

**Effect of topology and visibility on search performance**

The reason we picked Grand Canyon National Park for our experiment is because this parks has the largest number of missing person cases annually in the US, thus it would provide a critical real-world context for our study. To ensure our findings were broadly applicable, we chose four distinct locations within the park, each characterized by unique topographical features: one with multiple trails in the probability of area (POA), another featuring a valley with a single trail, a third with flatter terrain, and a fourth near the Colorado River. We anticipate that prior knowledge about the terrain and the missing person will enable the teleoperator to navigate relatively close to the target, regardless of the varied topography. However, in conditions with reduced visibility, such as dense vegetation or fog, we expect an increase in false positives, which could likely be addressed by flying slower and at lower altitudes, though this would extend the time required to locate the missing person.

1. Your study focused on UAVs in a wilderness search context. How might the movement-knowledge relationship differ for ground-based or aquatic robotic platforms?

We have added the following text in section 9 (conclusion and future directions)

Our hypotheses regarding movement-based inference of teleoperator state can be extended beyond UAVs to ground and aquatic robotic search operations, though each situation present a unique set of challenges. Prior research has already demonstrated the feasibility of inferring operator states from robotic movement patterns in these environments. For instance, studies have successfully estimated operator knowledge from ground robot trajectories [1], distinguished between novice and expert operators by analyzing movement variability [2], and assessed cognitive workload through metrics like end-effector speed, error rates, and energy consumption [3].

For ground based and aquatic search, the key differences lie in terrain complexity—obstacles, vegetation, and uneven surfaces necessitate slower, more deliberate movements compared to aerial systems. These constraints will lead to different movement patterns, such as hesitation, path replanning, or frequent stops reflecting uncertainty in situational awareness and increased cognitive load. Such constraints may enhance the detectability of operator state.

[1] Rafal

[2] Operation Status of Teleoperator Based Shared Control Telerobotic System

[3] Performance metrics outperform physiological indicators in robotic teleoperation workload assessment

1. What implications does your work have for operator training? Could movement patterns be deliberately trained to improve coordination with autonomous systems?

We added the following paragraph under the discussion section

**Implication for operator training**

The strength of our movement-based inference approach lies in its ability to decode natural, unmodified behaviors that inherently reflect operator state. Since movement patterns like turn rates, speed variations, and hesitation behaviors emerge organically from an operator's knowledge and cognitive load, there is no need to train operators to consciously alter or exaggerate these cues. This preserves intuitive human-robot interaction while reducing additional training burdens.

While our primary approach focuses on passive interpretation of natural movements, there exists potential to deliberately incorporate certain trained nonverbal cues for more explicit swarm control. Operators could be taught specific gesture-like movement patterns that autonomous systems would recognize as direct commands, effectively creating a hybrid control scheme that combines both natural inference and intentional signaling.

1. It would be beneficial to consider incorporating references to these attached papers in your current work, as they offer relevant methodologies for analyzing robot movement and fault detection in mechanical systems. The singular spectrum analysis approach for detecting oscillations in robot encoders and the synergistic method combining SSA with structured algorithms could provide valuable context for your teleoperator state inference framework, strengthening the technical foundation of your research.
   * A new synergy of singular spectrum analysis with a conscious algorithm to detect faults in industrial robotics." Neural Computing and Applications.
   * Detecting feeble position oscillations from rotary encoder signal in an industrial robot via singular spectrum analysis. IET Science, Measurement & Technology, 14(5), 600-609.

Not sure how these are helpful

Reviewer #2: The concern of the paper is important, but the key novelties of the paper has not been properly presented and justified. Please consider the comments below to improve the paper further:

1. Key contributions of the paper should be expressed clearly and then the major findings of the paper should be provided.

The contributions of this work are as follows: (i) we conduct experiments to test the hypotheses that movement features of a teleoperated UAV are dependent on prior knowledge of missing person speed and terrain, cognitive load, and situational awareness during missing-person search in a large virtual environment that realistically mirrors the Grand Canyon Park; (ii) we design an LSTM network to classify prior knowledge and a linear regression to estimate situational awareness from movement cues and identify the observation window that maximizes the classification accuracy; and (iii) building on the results from the experimental study, we validate human-swarm interaction strategies that adapt a swarm algorithm to regulate swarm assistance in search by using inference of teleoperator prior knowledge and situational awareness.

The study's major findings are:

* 1. Teleoperators' prior knowledge and situational awareness can be effectively inferred from UAV movement speed and turn rate.
  2. Cognitive load has a weak correlation with speed, freezing time fraction, and turning while still fraction.
  3. Adaptive search strategies has lower time to find, with large autonomous swarms the time difference is as high as 150s when compared to human only search.
  4. Search success is higher when prior knowledge is present in teleoperators.

1. Please improve the equations by adding brief insights about them.
2. Equation 6

The robotic agents follow a collective behavior model loosely based on the zonal model [Couzin]. This governs agent motion through three spatially-defined interaction zones surrounding each individual: (1) a repulsive zone maintaining minimum inter-agent separation distances, (2) an alignment zone where agents match their orientation with neighbors, and (3) an attractive zoneprompting agents to approach more distant group members. These zonal interactions - repulsion, alignment, and attraction - collectively produce emergent swarm coordination while preventing collisions, effectively mimicking the self-organized movement patterns observed in nature.

1. Please specify the kind of uncertainties. They can be internal or external, parametric or non-parametric, constant, characteristic or random. Determining their structures and amounts are challenging in the real time applications.

In limitations and other places

1. The critical review of the recent and related works are not quite strong. More recent works can be discussed in Introduction and the paper should be linked to literature of the topic addressed:
   1. Quantized Iterative Learning Control of Communication Constrained System with the Encoding and Decoding Mechanism, Transactions of the Institute of Measurement and Control;
   2. Repetitive process based indirect-type iterative learning control for batch processes with model uncertainty and input delay, Journal of Process Control;
   3. Dynamic Event-Triggered Consensus Control for Interval Type-2 Fuzzy Multi-Agent Systems, IEEE Transactions on Circuits and Systems I: Regular Papers;

In this sense, also due to generality, it could be the object of a brief consideration focused on the advances on the topic and make relation with these papers, which have to be discussed in Introduction section in the context of a more comprehensive literature review.

1. The manner of writing references should be harmonized and everything should be checked in detail. Namely, in many references are missing data, such as DOI numbers, pages, volumes and issues, or already entered data are incorrect.
2. Performing a comparison-based analyses with a recent and related approach under the equal conditions could help to improve and justify the contribution of the paper.
3. How the main control parameters will affect the control performance such as the control signal level, the control speed, the control consumption, etc. Please discuss this issue in appropriate places.

Control effort: