



National Aeronautics and Space Administration

True Partnership: An Actual Human Machine Team

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Why teams ...

- Autonomous systems will help fully realize societal benefits of aviation—on-demand transportation for all, rapid first responder response, environmentally optimized flight
- For this to occur:
 - (1) Need a *combination* of smart agents and humans working together
 - (2) Need to *maximize* the capabilities of each member
 - (3) Need to *work together* as teammates with shifting and adaptable responsibilities as opposed to a prescribed and rigid command structure



- Achieve best possible system performance → Need to integrate best capabilities of the machine (autonomy) and humans
- Based on experience of highly functional human teams → Can be achieved through **teamwork***

*To achieve the intended benefits of increasingly-autonomous functions ... will require an ability that does not exist today to **effectively and safely team humans with autonomy.**

Pritchett, A.R., et al. (2017). Research and Technology Development for Human-Autonomy Teaming A Literature Review. NASA Contractor Final Report, NNL16AA07C.

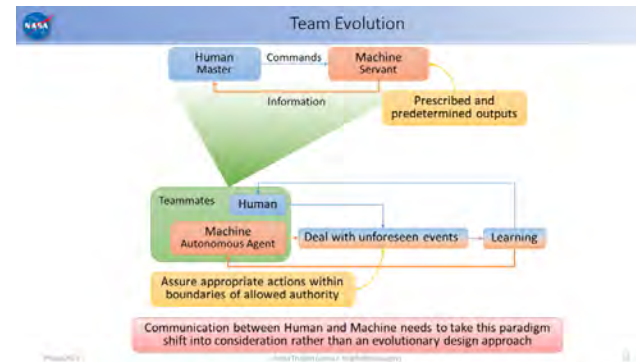
- Current – Master/servant
- Need to move to teams
 - Why/benefits
 - What makes a team
 - Team building blocks (cross training)

- Team evolution/types of teams
 - Informational → Master/servant
 - Automation → Strict hierarchy
 - Autonomy → Teammates with roles (with cross training)

- Other examples
- Summary

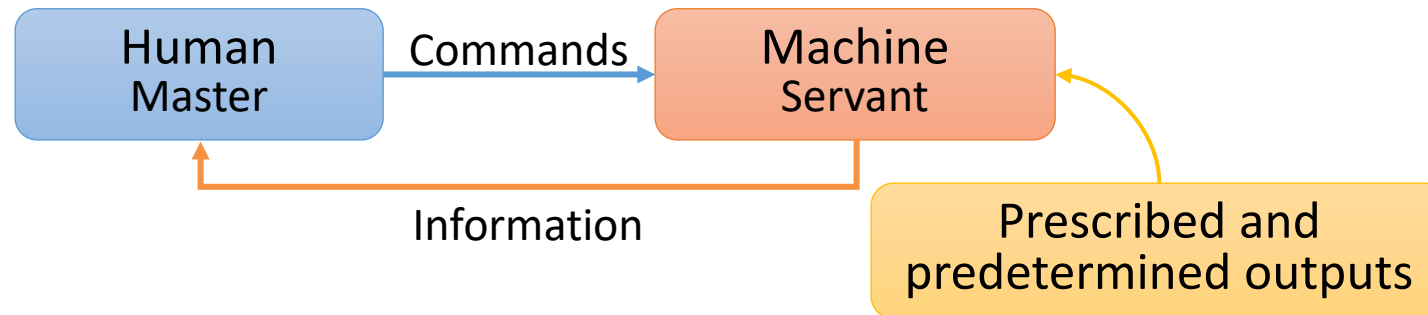
Currently ...

- Most research on human-autonomy teaming (HAT) assumes HUMAN master → machine (autonomy) servant
 - m:n
 - 14 CFR § 91.3 (a): The pilot in command of an aircraft is directly responsible for, and is the final authority as to, the operation of that aircraft
 - HEOMD-405 Capabilities Integration Gap List:
 - ☑ Crew needs to interact efficiently and independently with autonomous and robotic systems → Beginning to define roles between agents to function as a team
 - ☒ ... deep-space crew to operate independently from ground-control to interact with and manage autonomous lunar or Martian assets → BUT back to human as a master and machine as a servant



Other Examples

- Most research on human-autonomy teaming (HAT) assumes HUMAN master → machine (autonomy) servant
 - **m:N**
 - US federal aviation regulations: The *pilot* in command of an aircraft is directly responsible for, and *is the final authority* as to, the operation of that aircraft (14 CFR §91.3 (a))
 - Human Exploration and Operations Mission Directorate:
 - ✓ Crew needs to interact efficiently and independently with autonomous and robotic systems → Beginning to define roles between agents to function as a *team*
 - ✗ ... **deep-space crew** to operate independently from ground-control to interact with and **manage autonomous** lunar or Martian assets → BUT back to human as a master and machine as a servant (HEOMD-405 Capabilities Integration Gap List)



However ...

- As machines become more capable, human master–machine servant will *not* achieve true teaming and collaboration
- To realize full benefits of autonomy*, non-human agents will need to be on par with humans in order to build a team
 - There needs to be a “boss” within each level that decides on goals/mission/requirements
BUT
 - “Boss” could be human or non-human agent



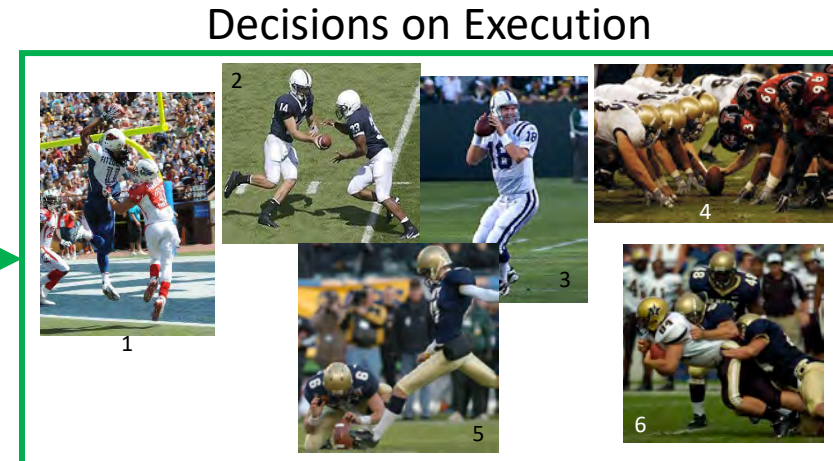
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*Autonomy results from delegation of a decision to an authorized entity to take action within specific boundaries. ... To be autonomous, a system must have the capability to independently compose and select among different courses of action to accomplish goals based on its knowledge and understanding of the world, itself, and the situation.

Report of the Defense Science Board Summer Study on Autonomy, June 2016 (p. 4)

Team Requires Each Agent to ...

- Make decisions on how to accomplish individual mission/goal
 - Requirement defined *not* methodology
- Implement those decisions without obtaining permission
- Communicate and cooperate with other pertinent agents in the system
- Specialization with some cross over → redundant heterogeneity*
- Boss is on-the-loop



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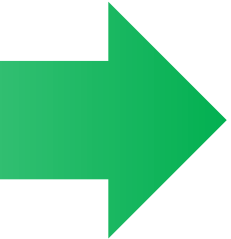
*Too much diversity can undermine itself, but too little diversity and you're not likely to get any unique viewpoints. There's no novelty. How Diverse Should Your Team Be?, February 2015 (<https://insight.kellogg.northwestern.edu/article/how-diverse-should-your-team-be>)



Possible Improvements ...

For the system:

- Improved situation awareness
- More accurate mission execution models^{1,2} based on current conditions
 - Ability to better manage uncertainty
- More complete understanding of actions



Better team decision making



Improved team performance

¹Promotes better understanding of teammates behaviors and promotes understanding of outcomes and inputs they are based on, not internal algorithms of the agent (e.g., ABS braking system – driver does not know algorithm for applying precise pressure for given break pedal input and road condition)

²[Y]ou've got to have multiple models — because if you just have one or two that you're using, ... *you'll torture reality so that it fits your models*, or at least you'll think it does . . . And the models have to come from multiple disciplines — because *all the wisdom of the world is not to be found in one little academic department*. Charlie Munger, Speech at USC Business School, 1994



Teammates

Communication:

- Same understanding of goals, objectives, current situation, and plans
- Machine behavior needs to be transparent to human teammates

Trust:

- Experience
- Predictable behavior

A team is a group of people who *trust* each other
Simon Sinek

Sacrifice:

- Local agent optimization is sacrificed for global mission optimization

Accountability is to a person
Simon Sinek

Team coordination stability is related to team performance and *situation awareness* ...

Demir, M., et al. (2019). Team Coordination and Effectiveness in Human-Autonomy Teaming. *IEEE Transactions on Human-Machine Systems*, 49(2), 150-159. <https://doi.org/10.1109/THMS.2018.2877482>

To remain flexible and adaptive, ... teams must maintain a balance between overly structured and completely random *interaction* patterns.

Gorman, J. C., et al. (2012). Measuring Patterns in Team Interaction Sequences Using a Discrete Recurrence Approach. *Human Factors*, 54(4), 503-517. <https://doi.org/10.1177/0018720811426140>

[T]here is no team knowledge, but rather *individual knowledge of the teammates*.

Demir, M., et al. (2020). Understanding Human-Robot Teams in Light of All-Human Teams: Aspects of Team Interaction and Shared Cognition. *International Journal of Human-Computer Studies*, 140, 7. <https://doi.org/10.1016/j.ijhcs.2020.102436>

Both real-time awareness and knowledge of the task are necessary for team *coordination*.

Demir, M., et al. (2020). Understanding Human-Robot Teams in Light of All-Human Teams: Aspects of Team Interaction and Shared Cognition. *International Journal of Human-Computer Studies*, 140, 7. <https://doi.org/10.1016/j.ijhcs.2020.102436>



Teammates

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Aspects of Endsley's Situation Awareness model

Endsley, M.R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors*, 37(1), pp. 32-64.

<https://doi.org/10.1518/001872095779049543>

Trust:

- Experience
- Predictable behavior

Army Research Laboratory situation awareness-based transparency (SAT) model

Level 1: Purpose, process, and current performance and status

Level 2: Rationale or the agent's reasoning process

Level 3: Projections of future outcomes, uncertainty, likelihood of success, and performance history

Chen, J.Y.C., et al. (2014). *Situation awareness-based agent transparency*. (ARL-TR-6905). Aberdeen Proving Ground, MD: U.S. Army Research Laboratory. Retrieved from <http://www.arl.army.mil/arlreports/2014/ARL-TR-6905.pdf>.

Sacrifice:

- Local agent optimization is sacrificed for global mission optimization

NASA Human-Autonomy Teaming (HAT) research will provide HAT principles to enable m:N operations. Effective teams *require* supporting coordinating mechanisms: Appropriate **Trust** Calibration, Shared **Mental Models**, and Bi-Directional **Communication***



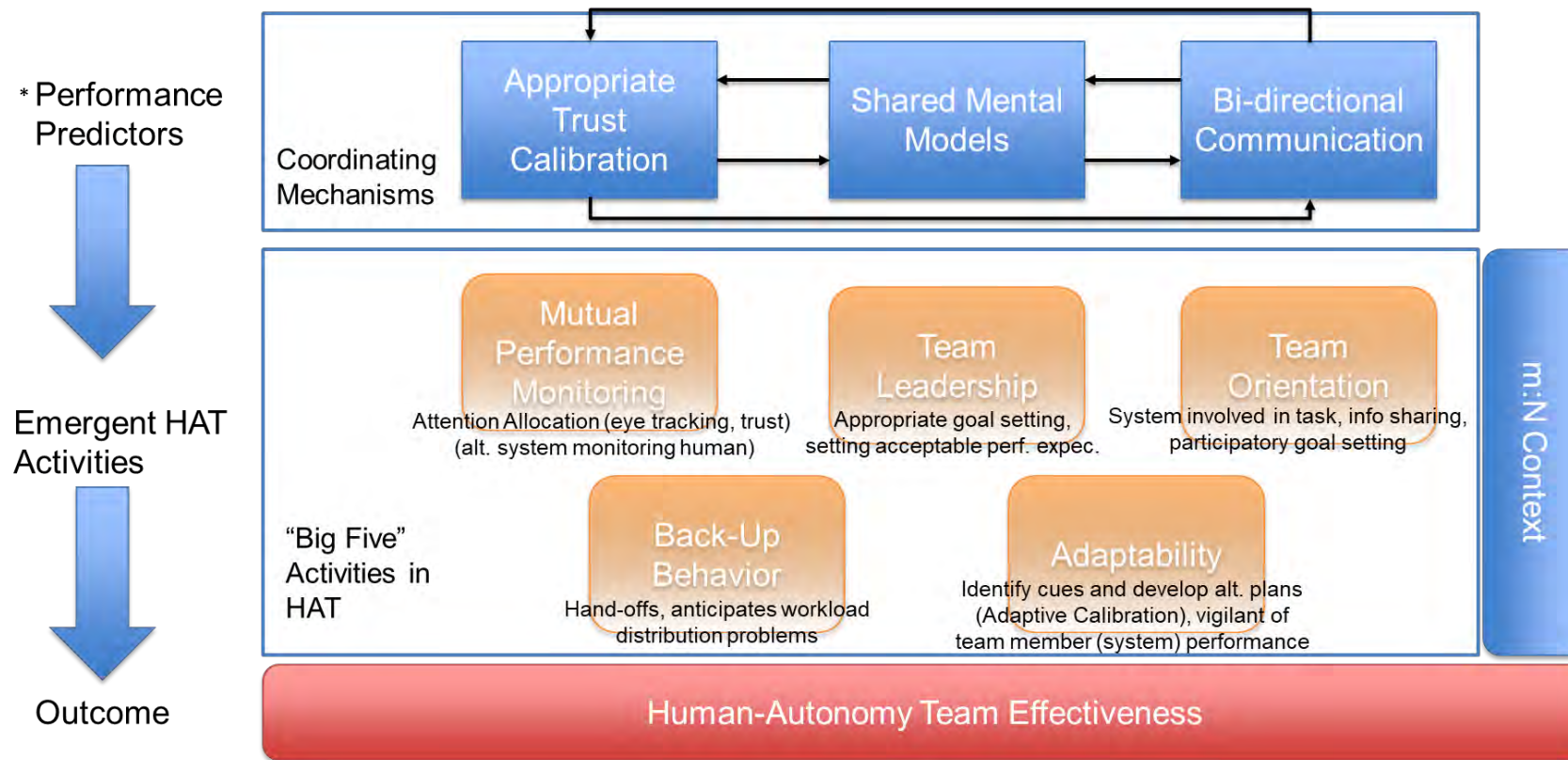
*J. Holbrook et al. (2020). Enabling Urban Air Mobility: Human-Autonomy Teaming Research Challenges and Recommendations. In *AIAA AVIATION 2020 FORUM*. <https://arc.aiaa.org/doi/abs/10.2514/6.2020-3250>

Human-Autonomy Teaming: Enabling m:N Operations

Trust is an inherent requirement in effective teams^{1, 2}. When team members (humans, autonomy) work interdependently they must be willing to accept a level of risk to rely upon each other to reach goals, contribute to team tasks, and cooperate confidently.

¹Holbrook, J., et al. (2020). Enabling Urban Air Mobility: Human-Autonomy Teaming Research Challenges and Recommendations. In *AIAA AVIATION 2020 FORUM*. <https://arc.aiaa.org/doi/abs/10.2514/6.2020-3250>

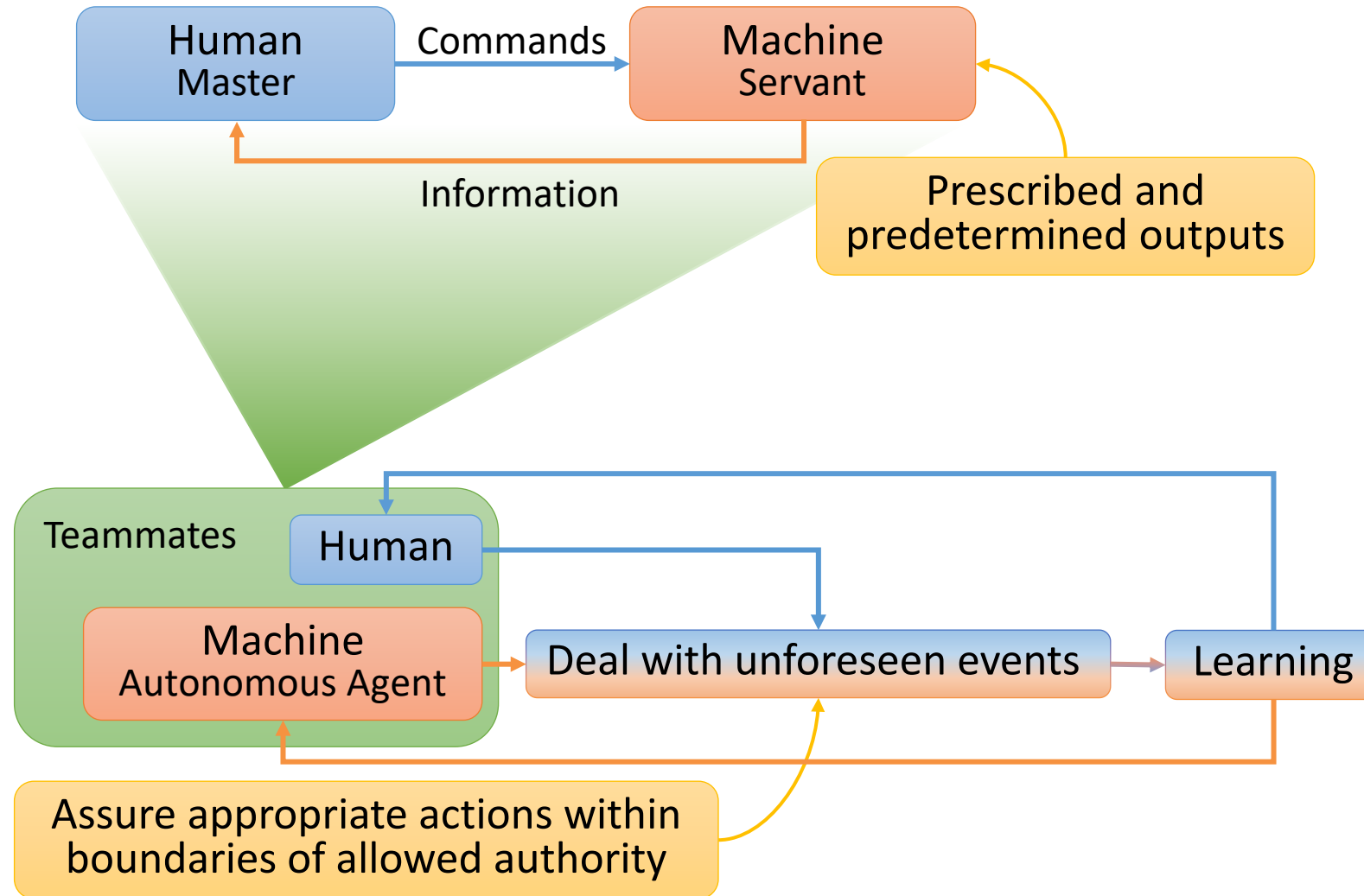
²Salas, E., et al. (2005). Is there a “Big Five” in teamwork? *Small Group Research*, 36(5), pp. 555-599. <https://doi.org/10.1177/1046496405277134>



*Except where noted, all figures created by NASA authors



Team Evolution



Communication between Human and Machine needs to take this paradigm shift into consideration rather than an evolutionary design approach

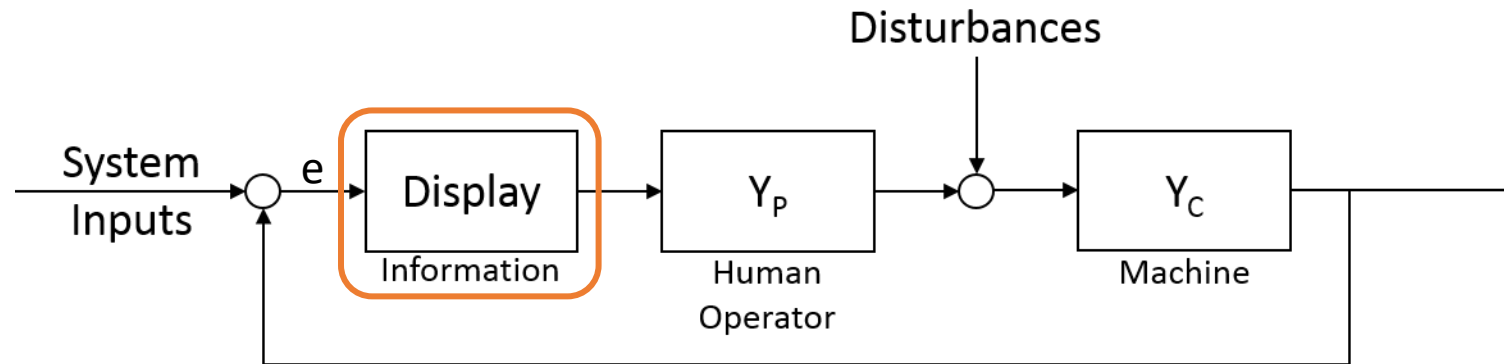


Standard ... Servant Providing Information

- Provide adequate information to appropriately maintain human controller situation awareness
- Minimum: provide information about current situation
 - Ecological interface design principles: constraints and relationships in system to be evident to operator

Human has direct control

- Execution of a function based on obtained information resides with the human operator



Training and Rules of Thumb:

- Operator implements them as appropriate

- Fly at highest practical altitude
- Avoid rapid, "high g"/high bank angle turns
- Use a glideslope that is a few degrees steeper than a normal approach

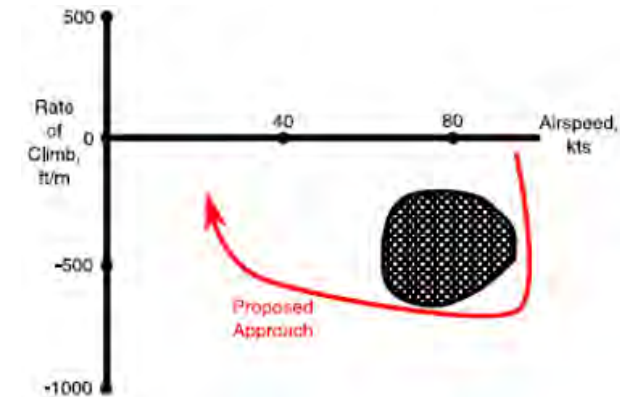
Noise Propagation Algorithm:

- Considers real-time blade vortex interaction and helicopter attitude
- Specific changes in helicopter attitude to decrease footprint now possible



- Ability to project actual noise footprint on ground

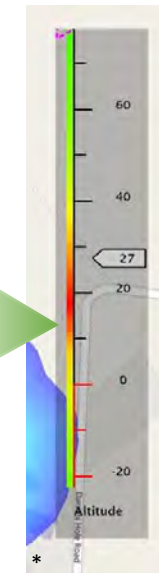
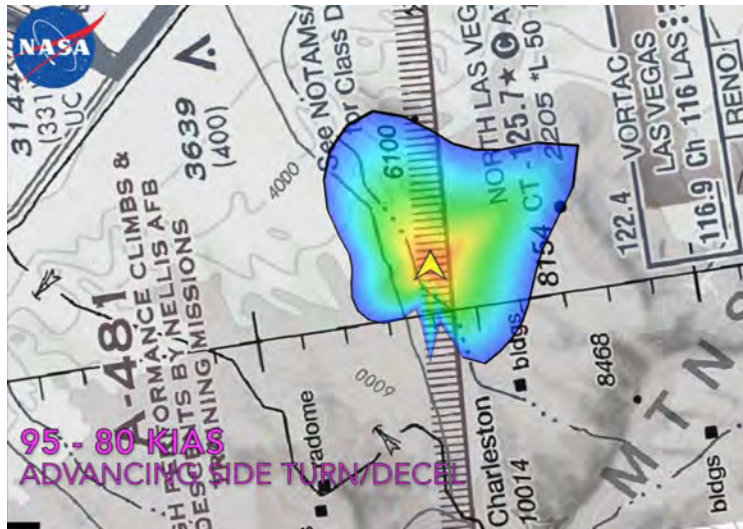
Possibility of becoming a teammate



Greenwood, E. (2017). Real time helicopter noise modeling for pilot community noise awareness. In *Noise-Con 2017*.



Greenwood, E. Aeroacoustics Branch, NASA Langley Research Center. Now Assistant Professor, Dept. of Aerospace Engineering, The Pennsylvania State University

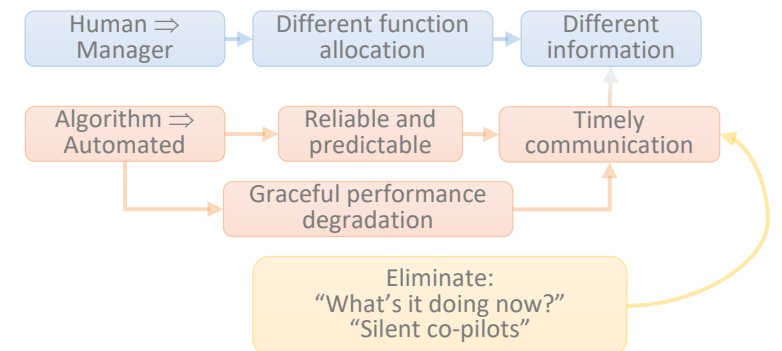
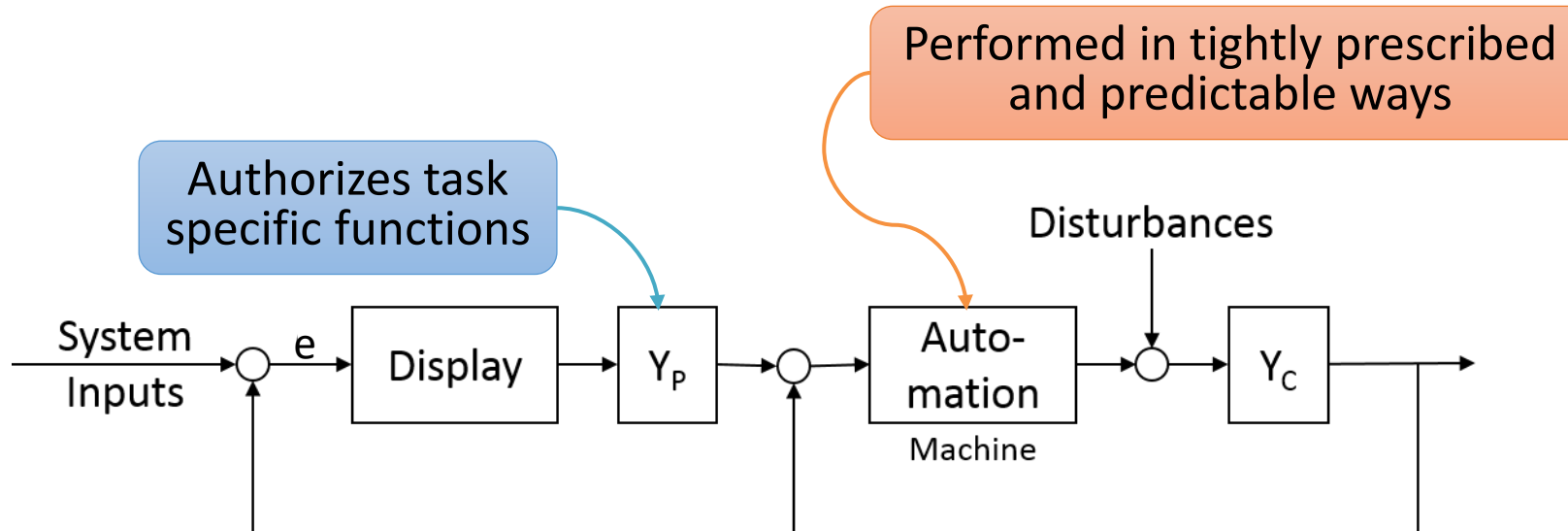


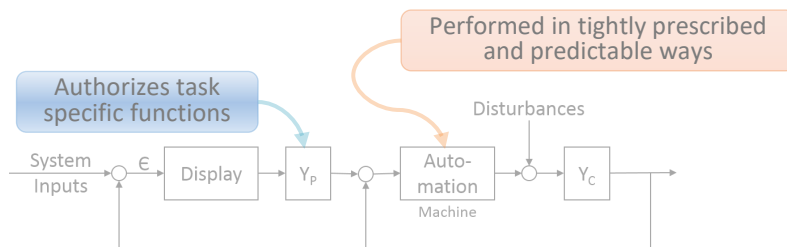
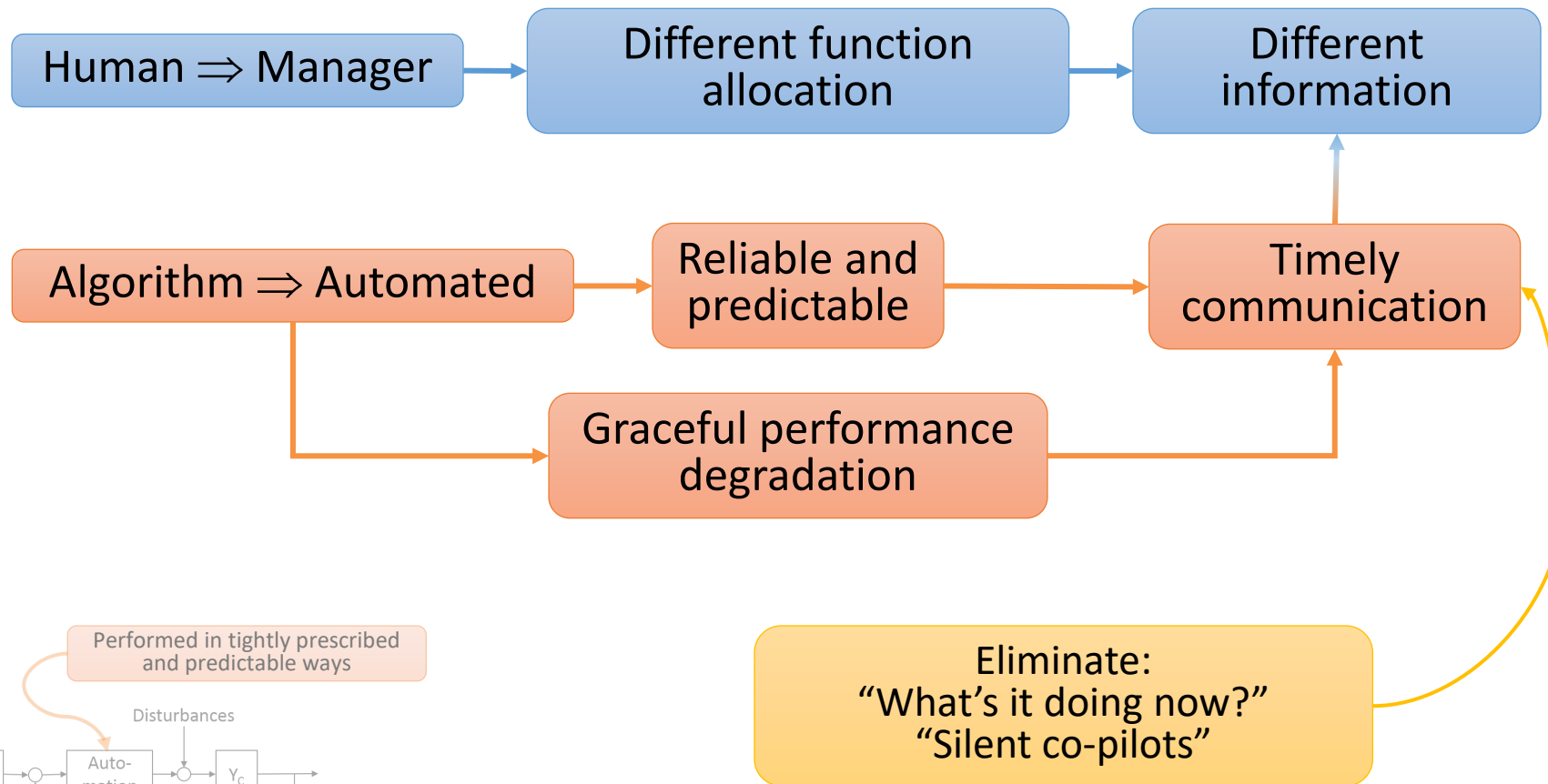
*Contains information from OpenStreetMap, which is made available at openstreetmap.org under the [Open Database License](https://openstreetmap.org/licenses/) (ODbL)

- Communication and trust most important for information system and teammates
 - Communication: How to decrease noise footprint
 - Trust: Noise footprint changes as expected with helicopter attitude; suggested maneuver will not introduce unsafe helicopter state

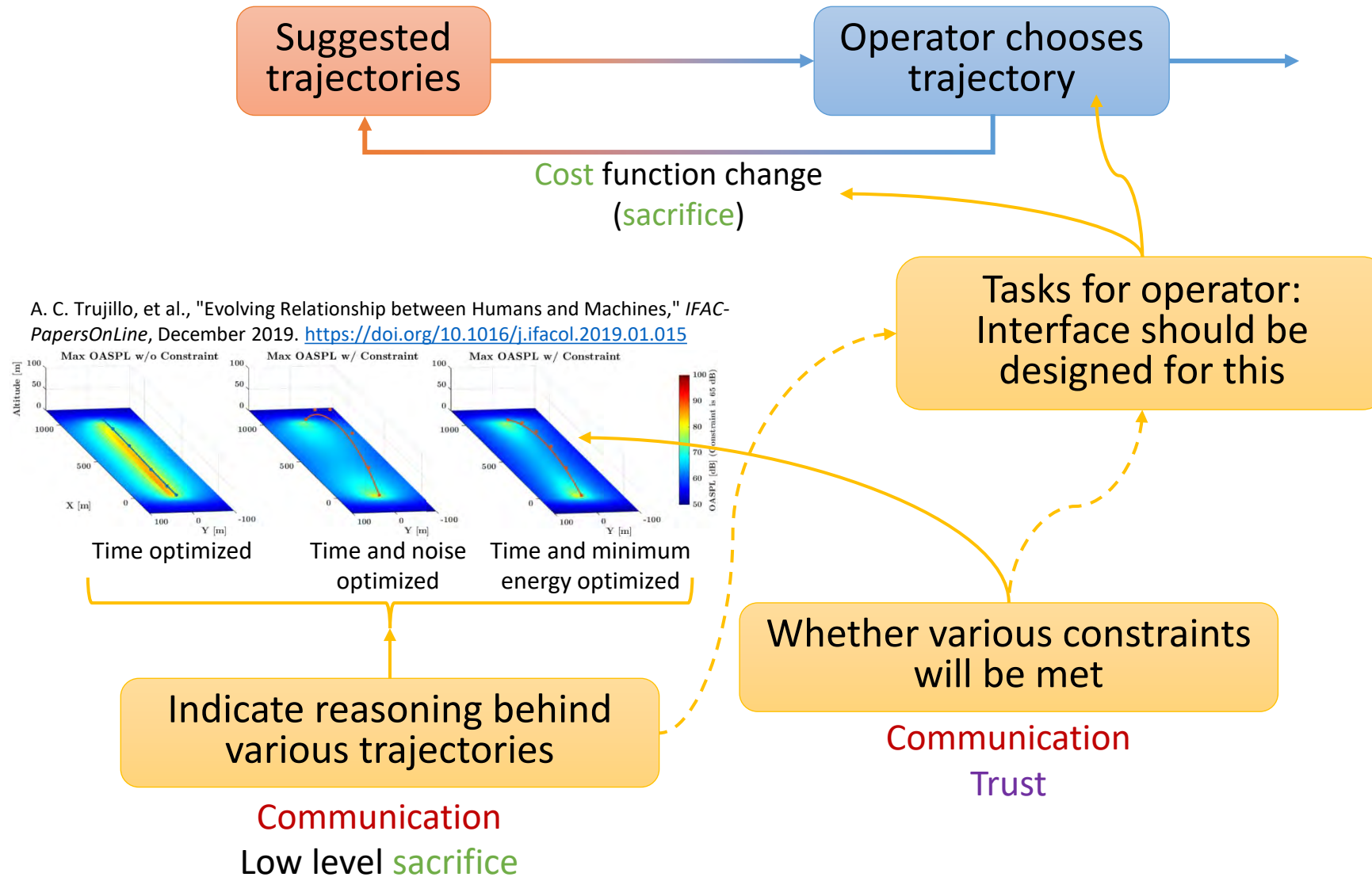


Currently ... Automation



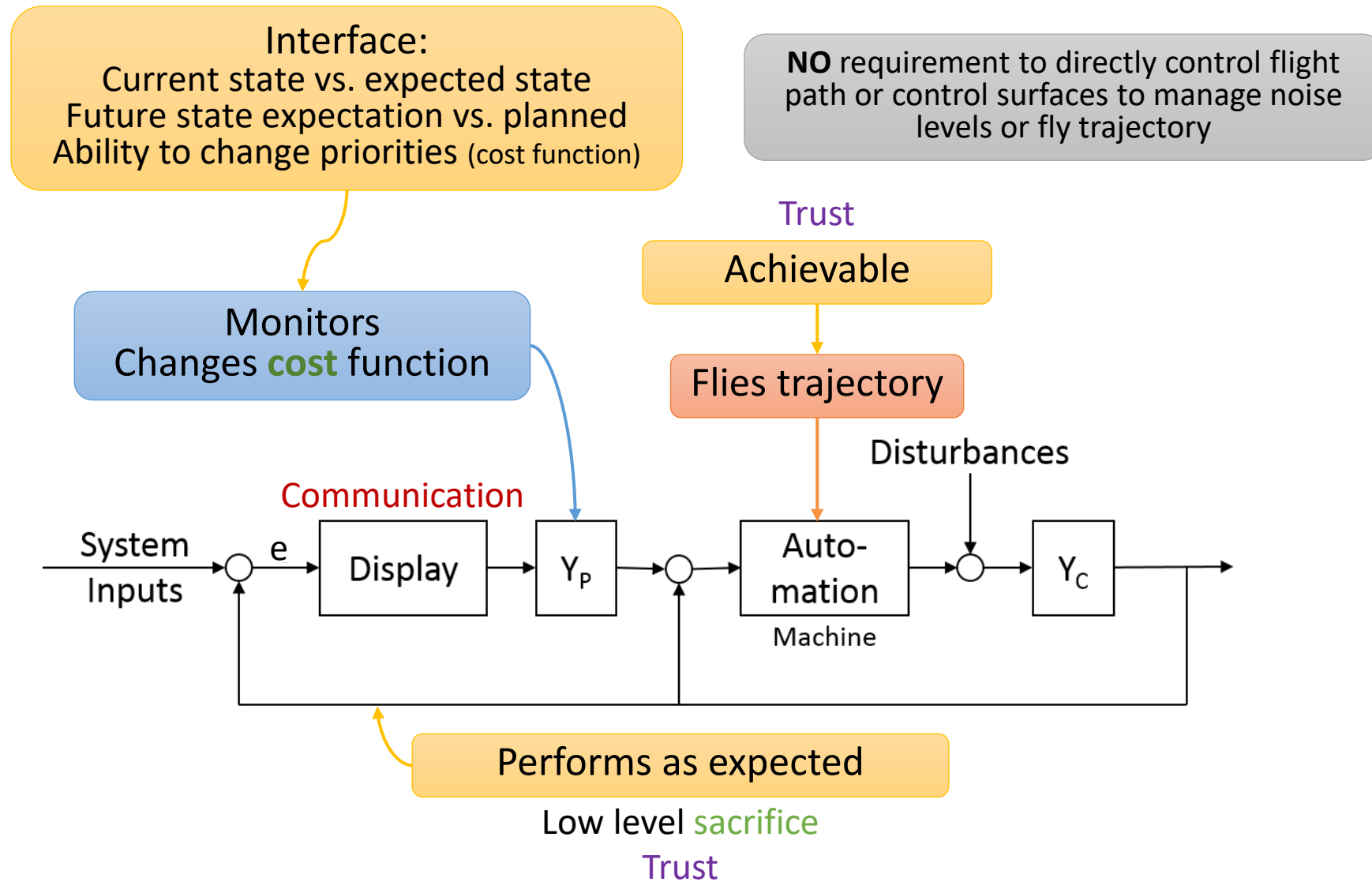


Noise Minimization Automation



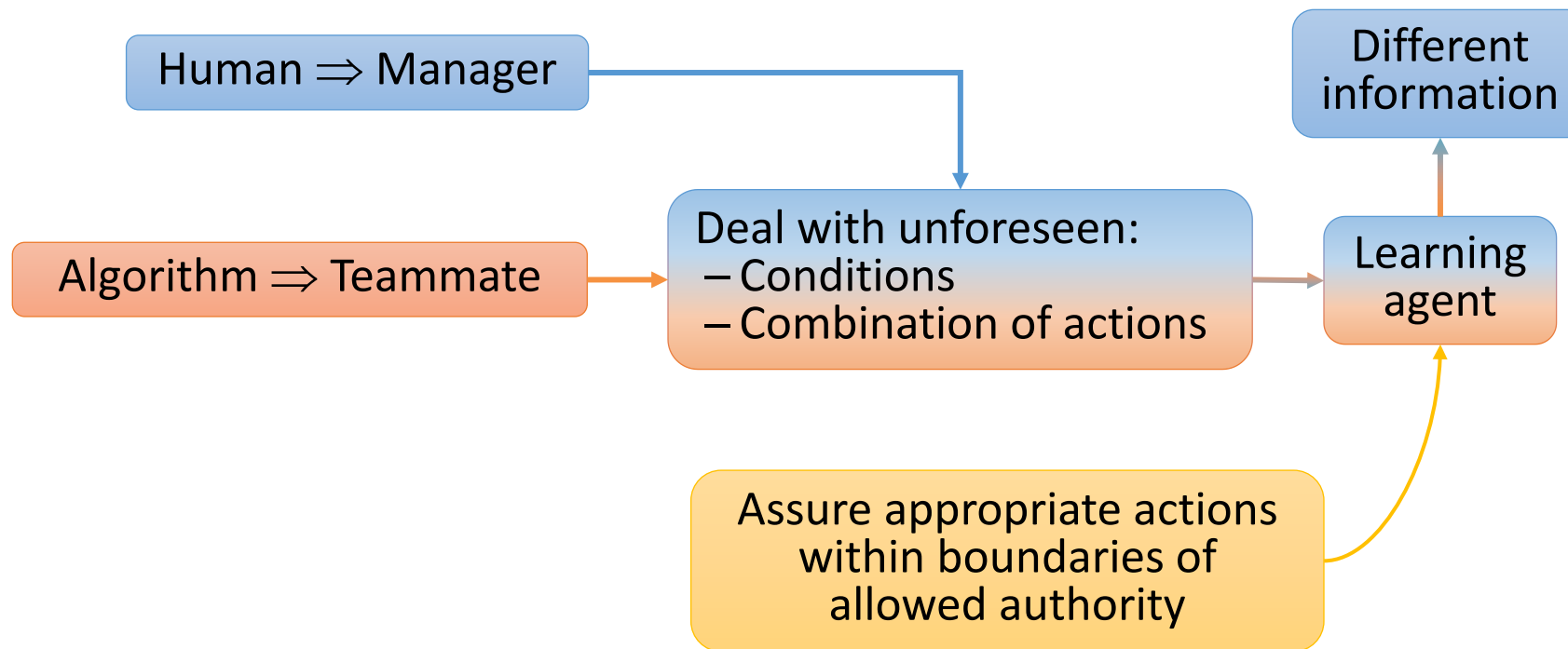


Noise Minimization Automation



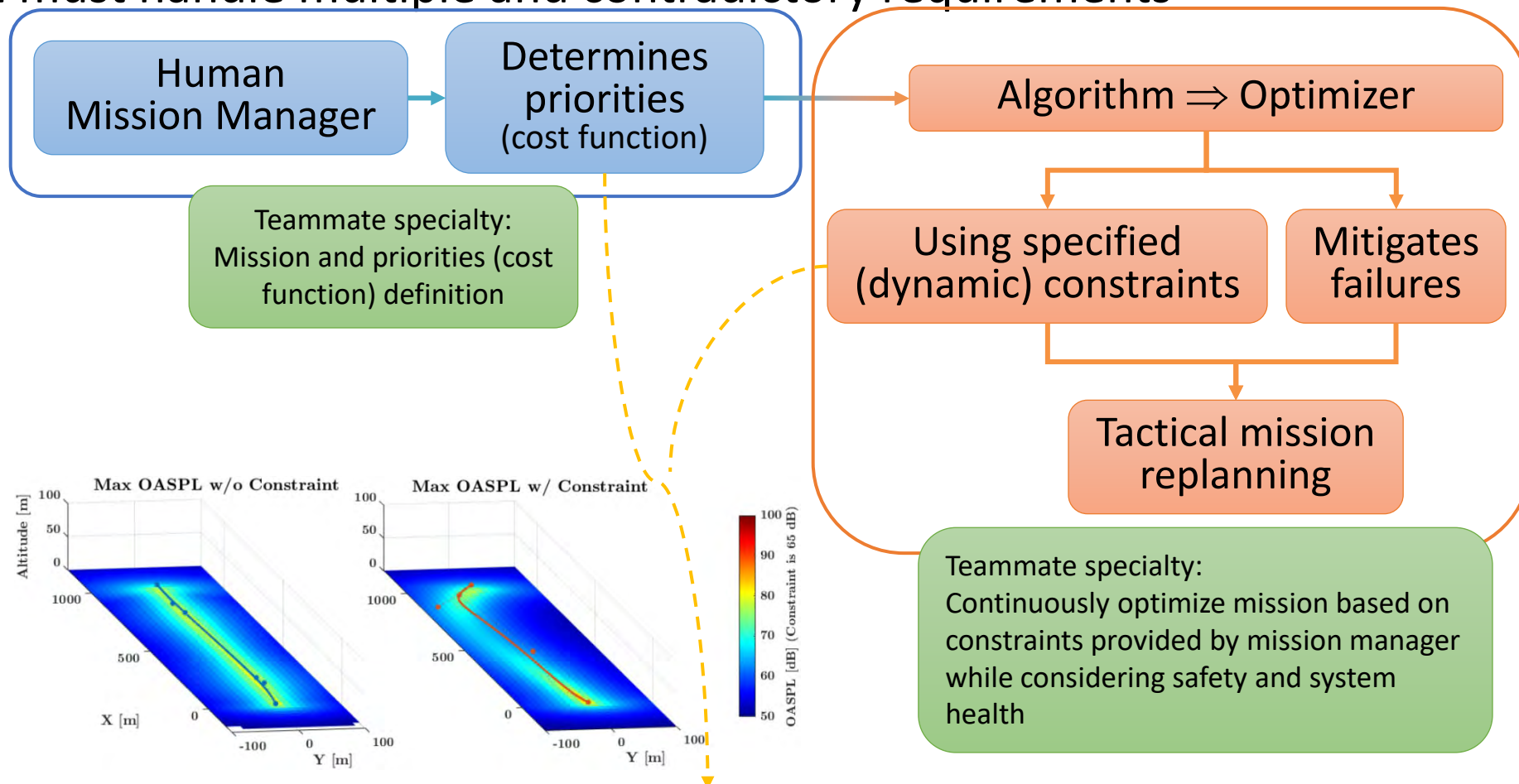


Moving Towards ... Autonomy



Mission Level

- **System** must handle multiple and contradictory requirements



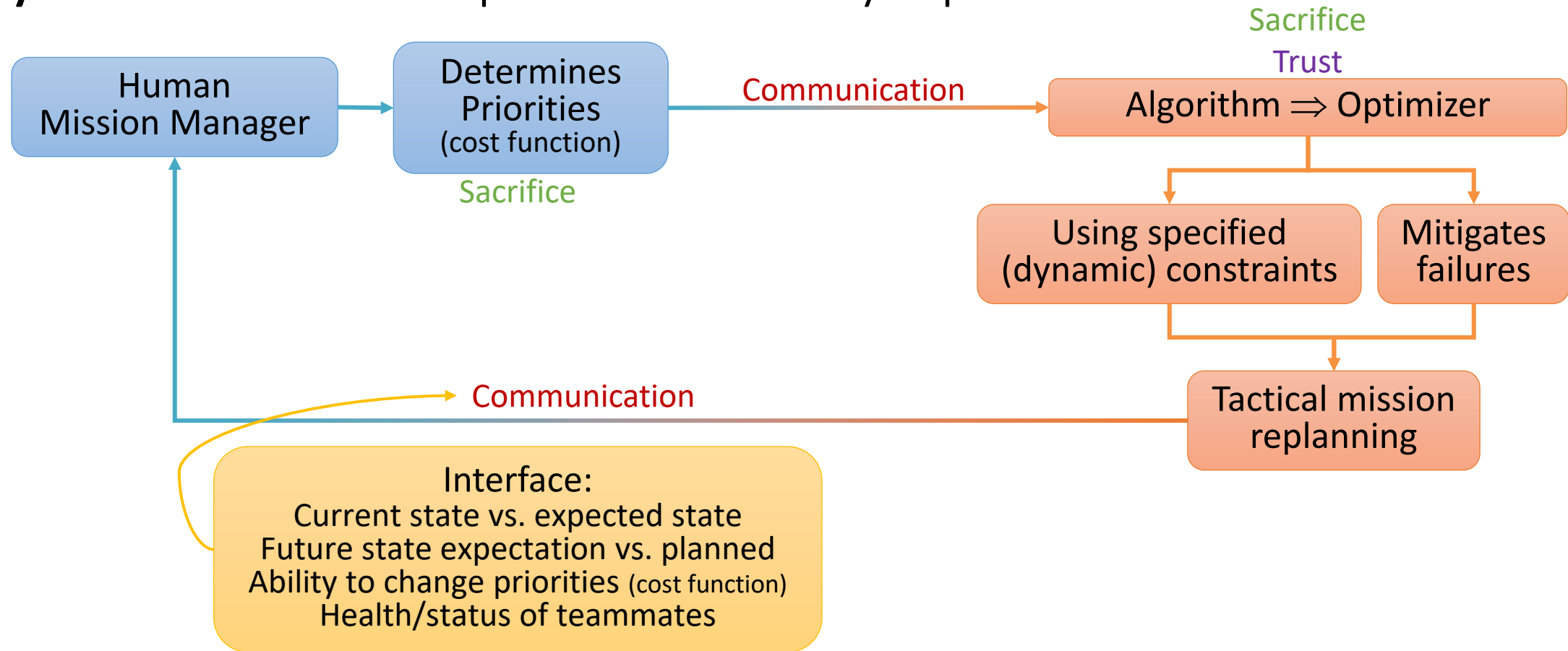
Mission performance (travel time), energy consumption, dynamic noise signature, restricted air space, etc.



Noise Minimization Autonomy – Teammates

Mission Level

- **System** must handle multiple and contradictory requirements



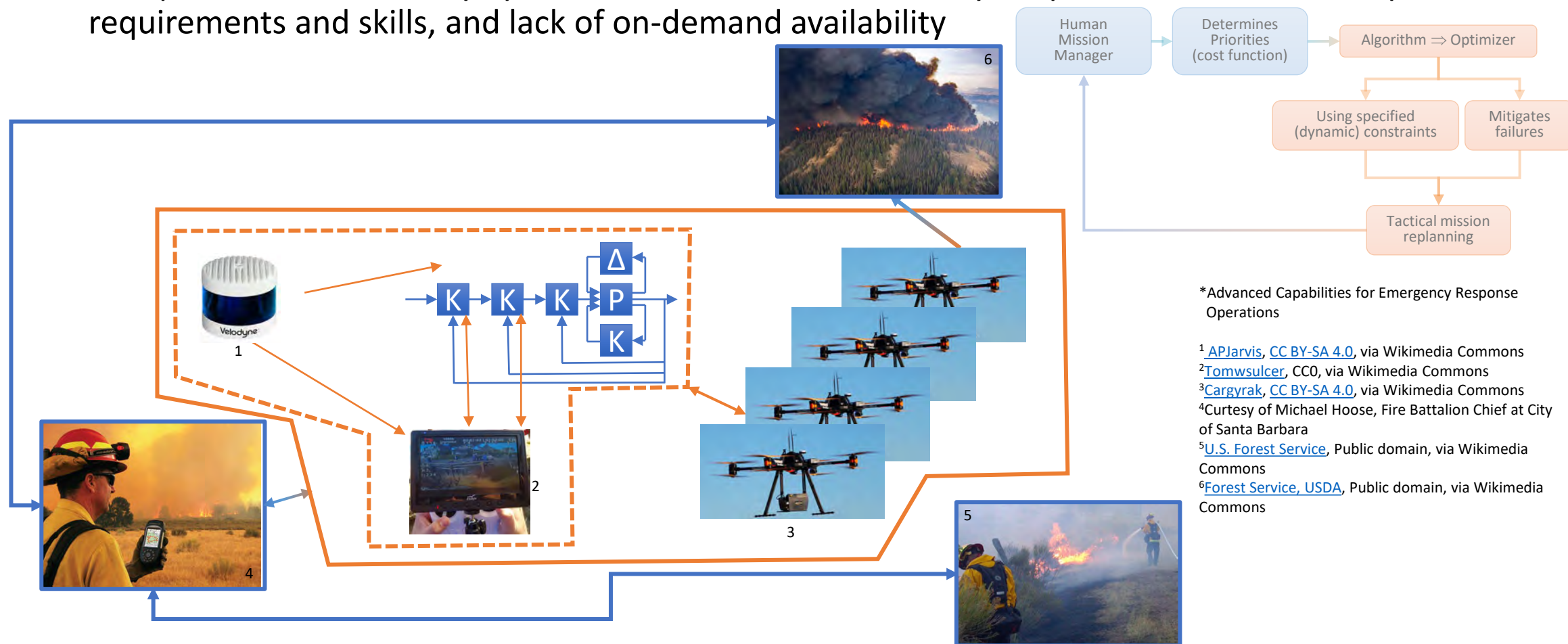
NO requirement to directly control flight path or control surfaces to manage noise levels or fly trajectory
NO requirement to review and accept changes to plan as long as within the given priorities (cost function)

Other Examples

Photo courtesy of Michael Hoose, Fire Battalion Chief at City of Santa Barbara



- Autonomy is a transformative capability that enables new approaches and provides new tools → Autonomy becomes a service
 - UAV potential is limited by operations in structured, relatively simple environments, manpower requirements and skills, and lack of on-demand availability



*Advanced Capabilities for Emergency Response Operations

¹ [APJarvis](#), [CC BY-SA 4.0](#), via Wikimedia Commons

² [Tomwsulcer](#), CC0, via Wikimedia Commons

³ [Cargyrak](#), [CC BY-SA 4.0](#), via Wikimedia Commons

⁴ Curtesy of Michael Hoose, Fire Battalion Chief at City of Santa Barbara

⁵ [U.S. Forest Service](#), Public domain, via Wikimedia Commons

⁶ [Forest Service, USDA](#), Public domain, via Wikimedia Commons

HAT research provides basic and applied research testbeds to study HAT-enabled m:N operations in live and virtual settings

HATTB (Human-Autonomy Teaming Task Battery): Used to evaluate the performance of participants as they monitor simulated autonomous objects while simultaneously performing various other predefined tasks

Learning adaptive agents
Team members

ROAM (Remote Operations for Autonomous Missions) UAS Operations Center: Research facility to support beyond visual line of sight (BVLOS) UAS operations

Mission Manager

HATT-B

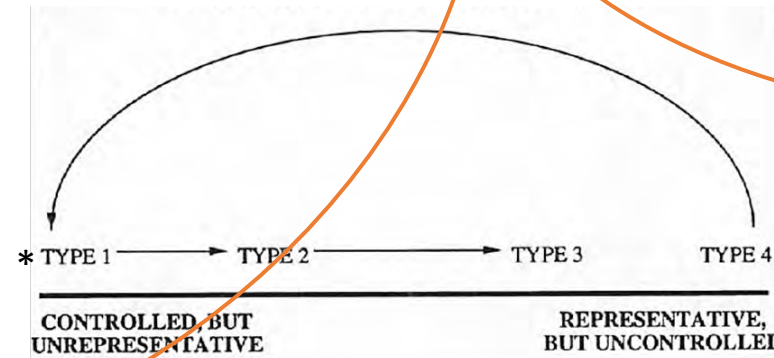


Experiments
(Basic) 1

MPATHx



Experiments
(Part-Task Sim) 2



HITL Simulations 3



Observational
Studies 4

MPATH



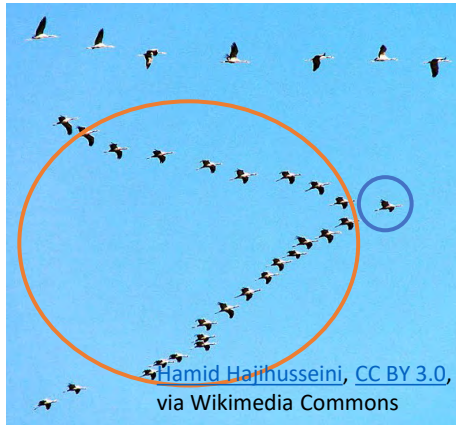
ROAM UAS
Ops Center
(Sim)

MPATH (Measuring Performance for Autonomy Teaming with Humans) Ground Control Station (GCS): Used to evaluate the performance of ground control station operators (GCSOs) using live and/or simulated UAS vehicles

*K. J. Vicente (1997), "Heeding the legacy of Meister, Brunswik, & Gibson: Toward a Broader View of Human Factors Research," *Human Factors*, vol. 39, no. 2. [10.1518/001872097778543822](https://doi.org/10.1518/001872097778543822)

Self-Organizing Dynamic Pods

Lead is
Mission Manager



Lead may change due to
changing conditions



Steindy, CC BY-SA 4.0, via Wikimedia Commons

Formation Flying (Air-Wake-Surfing)
<https://doi.org/10.2514/6.2020-1001>



Learning adaptive agents
Team members

Boeing Loyal Wingman: Combat drone capable of
flying alongside manned aircraft
([Graphic News \(March 24, 2022\)](#))



Performance Benefits

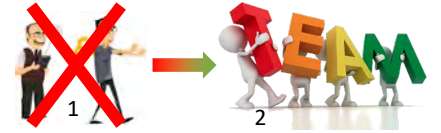
- Less workload for ATC → *Communicates* with current leader
- Fewer operators needed → Multi-agent pods (autonomous and piloted vehicles)
- More stable resilient *communication* → Pod internally *communicates* formation and formation changes

Team

- ATC *trusts* pod to follow leader
- Leader *communicates* ATC commands to rest of pod
- Pod *trusts* leader to *sacrifice* local (agent) optimization for system optimization

Moving from a Master-Servant to *Teammate* relationship with machines

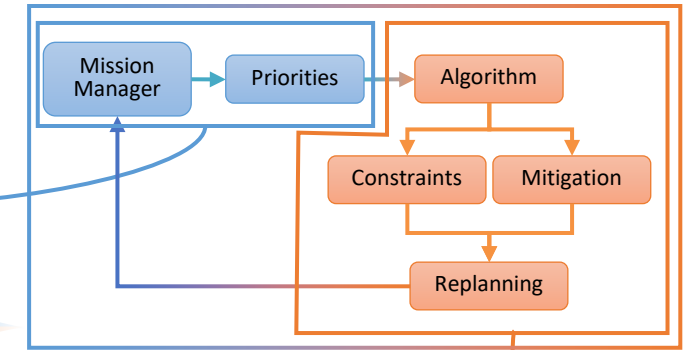
- New relationship requires different function allocation between humans and machines → new relationship should drive interface requirement rather than evolutionary adaptation of previous interfaces



To become a Teammate

- Systems will have to react to unknown/unforeseen events and uncertain dynamic environments

Learning adaptive systems



- To enable human to effectively team with an autonomous system requires predictable behavior and transparent decision making for *all* agents

Communication
Trust
Sacrifice

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²[This Photo](#) by Unknown Author is licensed under [CC BY-NC](#)



Challenges

To fully realize the societal benefits of aviation and to achieve best possible system performance, need best capabilities of the machine (autonomy) and humans and this can be achieved through **teamwork**

Several difficult challenges must be addressed

Do we need a paradigm shift?

- ... [A] *new approach* to the design of autonomous systems ... will allow them to **serve as an effective teammate**

United States Department of Defense, United States Air Force (2019). Autonomous Horizons: The Way Forward. Vol. 2, Human Autonomy Teaming. By Zacharias, Greg. Maxwell Air Force Base, AL. (Public Release Case No 2015-0267)

How do we maintain **trust** when “*my life is on the line, but yours is NOT!*”

How should we handle conflict resolution (**communication**) and final authority in complex situations?

Must consider (1) consequences, (2) decision time, (3) severity, (4) perceived competence, and (5) uncertainty → all may require **sacrifice**

- Characterizing uncertainty is the key to function allocation and provides a road map for when and why a human versus a computer could or should be part of the system.

Cummings, M. (2018). Informing Autonomous System Design Through the Lens of Skill-, Rule-, and Knowledge-Based Behaviors, *Journal of Cognitive Engineering and Decision Making*, Vol. 12, No. 1. [10.1177/1555343417736461](https://doi.org/10.1177/1555343417736461)



Thank you!



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