MULTIPLE SPACECRAFT FORMATIONS

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C0] LABORATING AUTONOMOUS AGENTS

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Identified as a critical technology for many of NASA's 21" century science missions, spaceborne optical interferometry permits the very high resolution and equivalent light collecting area of a single telescope, but at a lower cost. To accomplish this, separation of an interferometer's small collecting apertures by large baselines are required, of the order of tenths to thousands of kilometers. Thus the large separations require multiple spacecraft formation flying. A separated spacecraft optical interferometer concept, referred to as the New Millennium Interferometer (Blackwood, *et al.*, 1995; Colavita, *et al.*, 1996; Lau, *et al.*, 1996) is a simplified interferometer that demonstrates enabling technologies while still retaining science capabilities. It has been identified as a strong candidate for the third deep space mission (DS-3) of the New Millennium Program, a deep space technology demonstration program in which artificial intelligence (AI) will play a prominent role.[1] Other proposed separated spacecraft missions are the Terrestrial Planet Finder and Terrestrial Planet Mapper missions, as well as future exoplanet imaging and high resolution astrophysics formation missions.

The DS-3 instrument would be distributed over three small spacecraft in an equilateral triangular formation: two spatcraft would serve as collectors, directing starlight towards a third spacecraft, which in turn would combine the light and perform the interferometric detection. Due to the round-trip communications delay and close proximity operations of the three spacecraft, ground-in-the-loop controlling will compromise the effectiveness of the formation; onboard AI capabilities will be required for DS-3 autonomous precision formation flying. Each DS-3 spacecraft is envisioned to have identical capabilities and software for formation controls, with one designated as the "master". The spacecraft so designated is responsible for initializing, and maintaining the formation geometry, including determination of fuel-optimal formation maneuvers and retargeting, whether the formation maneuvers occur about the equivalent formation center-of-mass or about the apex of the triangular formation. Because they have identical software, the l-ok of the master can be assumed by one of the other spacecraft upon predetermined fault conditions.

In a multiple spacecraft configuration such as DS-3, mere cooperation is insufficient to ensure a stable configuration, adequate science return, and robustness when faced with unanticipated events, either from within the team or from the external environment. Cooperation entails parallel, as opposed to joint activities. Operating in parallel, multiple systems will not assume exclusive use of shared resources, nor will they *knowingly* perform an action that would interfere with the successful achievement of another agent's goals. This paradigm is not robust; when faced with the unexpected, goals can be easily abandoned, as there is no "shared mental state" to achieve a joint goal. When agents collaborate, they each have the same joint goal, are committed to its achievement, and by inference, to each other. They will actively avoid *interfering* with another agent's goals. Unexpected events, either from the environment, or from another agent's behavior will not automatically doom the joint goal; within the agents is a persistence towards goal achievement, and this entails helping the other agent, or assuming his duties, where possible.

Several theories of multi-agent collaboration (MAC) exist (reviewed in Wilsker, 1996), however it is proposed that an augmented Joint Intentions theory (Cohen and Levesque, 1991) would be most applicable to this

[1] The first New Millennium flight, DS-1, will have an onboard "Remote Agent" consisting of a RAPS-based executive, an IMPACT-based planner/scheduler, and a Livingstone-based mode identification and recovery engine.

domain, as it embodies Irony of the elements that are considered fundamental to team formation and maintenance In this modal logic-based theory, if a team of agents has a Joint Persistent Goal (J])(i) towards some goal, all agents are jointly committed towards the successful prosecut ion of the action(s) that will achieve the goal. They cannot just "change their minds" and abandon the goal They will persist over time towards achieving the goal. If an agent adopts the *private* belief that the goal has either been achieved or is unachievable, he has a *hard-wired* goal to have his private belief mutually believed by the ohm team members. Only then will the JPG be abandoned. Communication, then, is made an explicit requirement of this theory, in contrast with other MAC theories. In addition, goal persistence over time builds robustness into the team's act ions, especially when faced with the dynamic and unpredictable environment of space.

We represent multiple spacecraft as autonomous agents in the Joint Intentions framework for DS-3. "1'0 do so we must augment the existing theory. In particular, it is currently a two-agent theory, and would have to accommodate more than two agents. Also, in this real time environment, limiting goal persistence 10 a "maximum" length of' time would also be required By modeling spacecraft as autonomous agents in this theory, we believe that the robustness of a multi-spa cecraft configuration is enhanced because, in addit ion to mutual cooper at ion, there exists joint commitment to a sha red goal, and support for one another should anomalous behavior develop. Ultimately, this leads to incr cased confidence in achieving mission objectives.

References

Blackwood, G. and M Colavita. "Technology Development for Separated Spacecraft Interferometers", *JPL internal proposal*, June, 1995.

Cohen, P. and 1]. Levesque. "Teamwork", *Noûs* 2S(4), (I991), 487-512.

Colavita, M., J. McGuire, R. Bartman, G. Blackwood, R. Laskin, K. Lau, M. Shao, and J. Yu. "Separated Spacecraft Interferomete r Concept for the New Millennium Program", *SPIE Conference 2807*, 1)enver, CO., August, 1996.

Lau, K., M. Colavita, and M. Shao. "The New Millennium Separated Spacecraft Interferometer", *STAIF 97*, Albuquerque, NM, January, 1996.

Wilsker, B. 'LA Study of Multi-Agent Collaborate ion Theories", *(])1) (')llt)li.v)~('(l et.v USC-ISI Technical Report*, October. 1996.

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