Temporal Heterogeneity and the Value of Slowness in Robotic Systems*

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Abstract— **Robot teaming is a well-studied area, but little research to date has been conducted on the fundamental benefits of heterogeneous teams and virtually none on temporal heterogeneity, where timescales of the various platforms are radically different. This paper explores this aspect of robot ecosystems consisting of fast and slow robots (SlowBots) working together, including the bio-inspiration for such systems.**

I. INTRODUCTION

Roboticists have traditionally eschewed slowness for speed, focusing on how to make their platforms perform ever faster and faster tasks. In contrast to this, nature has found that in certain cases, being slow is better, or at least that the same ecosystem is successfully populated by slow animals alongside fast ones, i.e., there is wide variability or heterogeneity in terms of the time-scales on which the animals operate.

Common knowledge alludes to the wisdom of being slow, as evidenced in proverbs such as "slow and steady wins the race" (derived from Aesop's the "Tortoise and the Hare"), slow but sure", "slow down, you move too fast" (Simon and Garfunkel lyrics), and "haste makes waste" (an old adage). But why is that?

Under the banners of bio-inspired and bio-mimetic multi-agent robotics, we investigate if there is a general argument to be made for slowness in robotics. As the benefits of slowness manifest themselves over long time-scales, the general study of slow robots (SlowBots) in our case is anchored in persistent environmental monitoring tasks, with a particular eye towards precision agriculture and surveillance.

We focus explicitly on this shift of vantage point using biologically-inspired principles for designing and evolving networks of autonomous agents. In particular, the following key, inter-connected questions must be addressed to achieve an understanding of the value of heterogeneity in multi-robot teams:

- Temporal Heterogeneity: Robots operating at different time scales. In particular, SlowBots are introduced as a way of making explicit the benefits of using slow robots in conjunction with fast ones. Tree sloths, slow lorises, and natural ecosystems are used as inspiration for this work.

* Research supported by Office of Naval Research under Grant #N00014-15-1-2115.

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- General Heterogeneity Measures: Ultimately, a general theory of heterogeneous teams should be developed driven by biology but drawing inspiration from other fields, such as economics and sociology.
- Heterogeneous Multi-Robot Teams: A number of different aspects of heterogeneous multi-robot teams should be investigated, e.g., building on our previous research (e.g., [1]), in order to cover, characterize, and understand heterogeneity along different dimensions.

II. DIMENSIONS OF HETEROGENEITY

By now, we have become reasonably good at designing distributed control strategies for teams of networked agents in order to achieve particular tasks, such as covering areas or achieving geometric formations, e.g., [2-5]. These designs have moreover benefitted from influences from biology, in that both biomimetic and bio-inspired strategies have been developed for homogeneous as well as heterogeneous teams, [1,6-9].

Key to understanding the role of heterogeneity in teams of autonomous agents centers on a characterization of what heterogeneity actually means and what it brings to the table in terms of improved performance, robustness, or other team-level considerations. To this end, we are assessing the impact of heterogeneity along three different dimensions, namely temporal, spatial, and functional heterogeneity.

By functional heterogeneity, we simply mean agents that are endowed with different types of capabilities in terms of how the agents sense and interact with the world, or in terms of their computational or communications resources. One can argue that spatial and temporal heterogeneity are subsets of functional heterogeneity, but due to their prominence as well as special structures, we consider them as distinct categories. What is lacking is a more fundamental understanding of how and why different spatial capabilities are preferable, e.g., the way jungle ecosystems support and are populated by both bush-dwellers and tree-dwellers.

Time-scale heterogeneity plays a central role in our research in that we study teams of agents operating at widely different time-scales. In particular, and the focus of this paper, is the investigation of the role of slow robots leading towards how to formalize the value that can be derived from having slow robots co-existing with much faster ones.

III. APPLICATION DOMAINS

Although our research is of a foundational nature regarding the role that heterogeneity plays in multi-robot teams, the mission considered is that of persistent monitoring, whereby robots must be present in an environment for extended periods of time in order to detect, isolate, and even mitigate threats. Such a multi-robot mission could, for instance, be initiated by a requirement drawn from either the aftermath of a natural disaster (search and rescue) or the possible presence of a weapon of mass destruction (counter-terrorism) that requires the monitoring of an urban setting where a team of heterogeneous robots is looking for specific signatures (e.g., Chem-Bio-Radiological or Nuclear) that will ultimately require human attention. We have previously addressed counter-Weapons of Mass Destruction (C-WMD) missions for the Defense Threat Reduction agency and can leverage those multirobot missions here [10,11].

These types of requirements are neither far-fetched nor made up - they can for instance be illustrated through two real scenarios, namely the Fukushima disaster cleanup scenario and the search for WMDs in Iraq (Figure 1). The locations of the goals (victims/weapons) are not known in advance, but are detectable by well-defined sensory signatures. The urban settings are complex, predicating a need for heterogeneity and a coordinated multi-robot platform response (air and ground). In addition, they pose major risks to the platforms themselves (e.g., time-pressure, physical challenges, discovery, etc.), all the while sharing the goal of efficiently exploring varied terrain where a priori knowledge is weak or absent. The idea we exploit is to view such a disaster area as an ecosystem that can be populated by different types of autonomous agents akin to different animal species found in naturally occurring ecosystems.

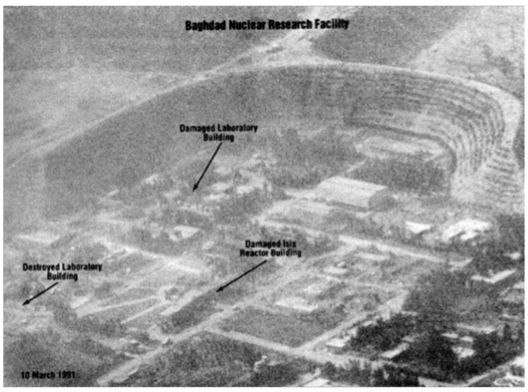

Figure 1: Top: Fukushima disaster.
Bottom: Baghdad Nuclear Research Facility (search for WMDs).
In both of these scenarios, autonomous agents could have significant use. [Wikipedia]

IV. RELATED WORK

The core technology that is making this research possible is the recent emergence of a relatively mature theory of how to coordinate control decisions across teams of networked agents. In fact, significant progress has been made over the last decade trying to understand networked dynamical systems in general, e.g., [3,12-15]. There is also work being perfromed on useful abstractions for human-swarm interactions. For example, in an earlier investigation by Arkin [16] motor schema were used as the interaction/abstraction, and the human operator acts on the team as an additional motor schema. In a similar manner, in [17], Goodrich views the strengths of biologically inspired entities as being influenced by the user. (Other similar approaches can for example be found in [18]).

V. BIO-INSPIRED SLOWNESS FOR ROBOTIC SYSTEMS

One can envision persistent monitoring scenarios where teams of robots are to be deployed in an area for a sustained period of time. Due to the long-term nature of their deployment, there should be performance benefits associated with having slow robots alongside fast robots in terms of energy conservation and even other performance reasons. In this section, we will discuss SlowBots, i.e., robots that act on a far slower time-scale than what it is normally expected in autonomous robotic systems.

Robotics researchers have considered snail-like locomotion [19] and soft-bodied slug systems [20] but not particularly for the added value that slowness itself can provide, as we do here. Other efforts considering the role of slow speeds include tendril [21] and continuum robots [22]. These provide mechanically slow modes of locomotion, but do not address the associated behaviors for the platforms as we do in this context. There has also been research in slow movements in humans and the use of resistive torques to reduce performance variability [23]. Finally there have been studies in human factors associated with determining safe slow speeds for robots performing alongside humans [24], but again this is not an issue for our research in the application domains we consider.

In fact, one primary dual-use application (aside from the WMD and search and rescue missions) envisioned within the context of persistent monitoring is precision farming, where robots are deployed on farms for long periods of time. In this case, we consider these SlowBots as long-term tenders of the environment, carrying out routine tasks among the plants: literally nipping things in the bud, conducting surveillance by monitoring for proper hydration, pests, and disease - all the while managing their energy effectively yet producing meaningful activity in support of the ecological niche in which they reside. They entrain themselves to the circadian rhythms of the crops, following them through diurnal and seasonal changes. Contrast this to the more common agricultural robotics approach, where larger machines conduct these operations periodically rather than continuously, and where heavy machinery moves between planted rows or trees, almost as an invading force rather than as a semi-permanent member of the ecosystem. The intent here is to develop a synergism between the environment and the robots that is both persistent and symbiotic.

Bio-inspiration for the development of the SlowBots is easily found and commonplace in nature, where our main exemplars include the Sloth and the Slow Loris, illustrated in Figure 2.

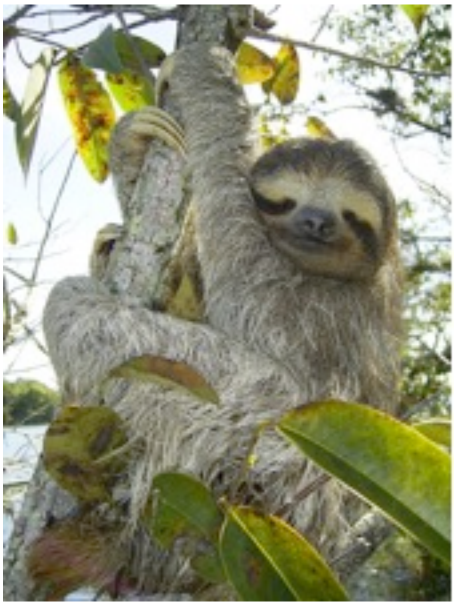

Figure 2: Slow mammals that serve as bio-inspiration for SlowBot Behavior [Wikipedia]
Top: Tree Sloth
Bottom: Slow Loris

A. The Tree Sloth

As an archetypal example of a slow animal, consider the Tree Sloth, whose range lies in Central and South America - a mammal well known for its slow locomotion. This strategy allows them to conserve energy:

"Their usage of energy saving food in connection with an unobtrusive life style turns them into complete models of energy saving among the mammals" [25].

But there are other reasons beyond pure energy conservation for being slow. It has been argued that their slowness allows them to use gravity to their advantage in locomotion and movement patterns [26]. On top of that, it has recently been argued that by being slow, the sloths become essentially "invisible" to certain predators, such as harpy eagles, where slowness has been called "the ultimate weapon in an evolutionary war" [27]. Indeed one group in Germany [26] posits that evolution has led them to use gravity to their advantage in locomotion and movement patterns [28]. In essence they are said to "walk under a tree":

"With their mode of life sloths are filling an ecological niche ... Sloths lead their lives in energy saving mode.... Their usage of energy saving food in connection with an unobtrusive life style turns them into complete 'models of energy saving among the mammals." [25]

It has been observed that despite their suspensory inverted orientation, their morphology and locomotion patterns are not all that different from other animals such as monkeys [28], but they use gravity for an advantage. As they have more vertebrae and a longer reach, they require less motion than animals of similar stature, resulting in energy savings. The need for new patterns of neural control of their musculature was reduced due to their evolutionary trajectory [28].

Physiological and behavioral studies of the sloth are available to guide our research [28,29]. Respiration rates are dependent upon their level of excitement or agitation. Their vision is relatively poor, being extremely shortsighted with low-levels of visual acuity and discrimination. Thus they use other senses for detecting danger, finding food, and locating other conspecifics [29]. Little is know about their courtship and mating behaviors, but that has little relevance for our robotics applications.

30.6% of their time involves waking behavior, while the remainder is sleep. The main patterns of activity are awake-exploring, awake-fixating, awake-alert, and behavioral sleep [29]. As stated earlier, their slowness affords them a sort of invisibility to predators [27]. This is an obvious advantage for surveillance tasks. Oddly, although they spend the vast majority of their time in treetops, they return to the ground to defecate, which makes them more vulnerable to predators [28]. Fortunately this is not an issue for robots.

B. The Slow Loris

The Slow Loris is a primate, unlike the sloth. But similar to the sloth, the Lorises also have developed slowness as an effective strategy, with energy conservation as one of the primary drivers [30-34]. They are found in South and Southeast Asia and Northern India and are exclusively nocturnal [34]. They are predominantly solitary animals (only 7-8% of their time is spent near other conspecifics [33,34]), but express a range of agonistic (attacks, pursuits, threats, assertion, fighting, staring, cringing, avoidance and subordinate behaviors) and associative (close proximity, physical contact, following, social exploration, social grooming, and social play) behaviors [33,34] involving spatial grouping and activity patterns. In captivity, dominant or submissive behaviors are not expressed [33]. The mating system is also unknown at this time. Specific nocturnal social interactions include allogroom (repeated licking), alternate click calls (between two conspecifics), follow (moving within 5m in same direction and pace) , and pant-growl (highly variable vocalization).

> *"They move slowly and deliberately, making little or no noise, and when threatened, they stop moving and remain immobile.... Slow Lorises have an unusually low basal metabolic rate, about 40% of the typical value for placental mammals of their size, comparable to that of sloths."* [35]

Alarm calls have not been observed among Slow Lorises although 8 different other types of communication calls have been noted related to contact/affiliation and aggression/defense [33,34]. Olfactory communication is an important channel, via urine marking or scent glands embedded in their elbows and anus. Although postural/facial communication is limited, grin and bare-teeth displays are in evidence, with the later present during agonistic and play behaviors [33].

Ethological studies have recorded the activity budgets and positional behaviors of the slow-climbing Mysore Slender Loris [36] and the Slow Loris in captivity [37]. The ethogram for the Slender Loris includes the following behaviors: Inactive, travel, forage, feed, groom, and other (e.g., auto-play hanging, vocalizing, urine washing and marking). They sleep almost entirely in trees in the daytime [34]. Very slow movement is observed during cautious sitting, standing, or hanging, sometimes with freezing of the animal lasting on the order of hours. Almost 90% of their active behaviors are devoted to dietary functions [37]. They have been seen to move swiftly when on the ground moving between trees [36]. Other studies elaborate the behavior of the Philippine Slow Loris [38] and the details of the animals' foraging behavior [39].

All of this data provides insights drawn from biology into the design of slow-moving bio-inspired behavior-based robotic controllers capable of navigating and existing within arboreal settings for tasks such as surveillance and plant tending. In fact, sloth and slow loris behavior profoundly influences the ongoing design of the SlowBots.

VI. SLOWNESS AS TIME SCALE SEPARATION

One way in which the value of having a mixture of slow and fast agents can be understood is in terms of how their time-scale separation allows for them to affect the same system, yet essentially be dynamically decoupled. Considering the sloth-eagle relationship, the eagle's sensory system operates at a faster time-scale than the sloth, thus rendering the sloth almost invisible to the eagle. The question is if such a separation of time scales can be understood in general terms for networks of autonomous agents.

As a motivating example, consider a collection of agents arranged in a linear network where the agents are trying to regulate their state, x_i, (could, e.g., be the positions of the agents) to approach that of their immediate neighbor, through where

$$\dot{x}_i = K_{fast}(x_{i-1} - x_i),\ \ i = 2, \ldots, N.$$

K_{fast} is the control gain, and N is the total number of agents in the network. These control actions can be thought of as the interior control loops in the network, akin to the route-level AQM (Active Queue Management) controllers in the transportation layer of the internet [40,41], or the consensus seeking terms in a multi-robot formation control scenario [3].

The interior controllers can be contrasted with an exterior, end-to-end controller. For example, one could imagine a human operator or a supervisory agent evaluating the state of agent N and using this state value to regulate the state at the beginning of the network, as was done in [42,43], (like the rate regulating TCP-action on the internet),

$$\dot{x}_1 = K_{slow}(r - x_N),$$

where r is a reference value. The resulting system is a cascaded control system, and the conventional wisdom is that the inner loop should be significantly faster than the outer loop, i.e., $K_{fast} << K_{fast}$.

In this particular case, the conventional wisdom is indeed "wise", as the system dynamics goes unstable when

$$K_{slow} > \frac{2K_{fast}}{N-2},$$

for sufficiently large N, i.e., time-scale separation is absolutely crucial for the high-level outer loop regulation to work, as shown in [44]. Moreover, as long as sufficient time-scale separation is achieved, the dynamics of the network, as perceived by the slow supervisory controller, is essentially an integrator, i.e., a simple system that can be easily controlled. This separation of time-scales across inner and outer loops in networks of dynamical "agents" can indeed be found in a number of applications, such as on the internet (AQM and TCP), in neural pathways where the feedback laws between the cortex and the thalamus are significantly slower than those found inside the cortex itself, on the power grid where slow set-point controllers are interacting with fast droop controllers for frequency regulation, or when human operators (slow) are to control teams of locally interacting (fast) agents.

We are exploring whether or not this time-scale separation is fundamentally useful in heterogeneous teams of agents. As already discussed, since sloths and hummingbirds coexist in the same ecosystem, we are investigating if the performance benefits associated with slow robots coexisting with fast robots can be understood in terms of the corresponding time-scale separation - essentially allowing the fast and the slow agents to co-inhabit the same ecosystem in a dynamically decoupled manner. For the agricultural application, this temporal heterogeneity will be present on the field in that SlowBots will tend to individual plants over long time-scales while one can envision larger, faster, ground-based robot tenders that can address the needs of repair and replacement of the SlowBots.

VII. Summary

Biological slowness provides value in nature in terms of energy efficiency, stealthiness, and other factors. It is an open question if similar benefits can be reaped within slow robotic systems. It is our contention, that within robot ecosystems where slow and fast robots co-exist and work towards a common goal, there is value added by exploiting temporal heterogeneity. We have presented both bio-inspired and control theoretic bases for this claim, and in ongoing research intend to establish it through theoretical analysis and experimental results conducted in simulation and actual robotic platforms.

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