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Autonomous mobile robots with lights ☆

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ABSTRACT

We consider the well known distributed setting of computational mobile entities, called robots, operating in the Euclidean plane in Look-Compute-Move (LCM) cycles. We investigate the computational impact of expanding the capabilities of the robots by endowing them with an externally visible memory register, called light, whose values, called colors, are persistent, that is they are not automatically reset at the end of each cycle. We refer to so endowed entities as luminous robots.

We study the computational power of luminous robots with respect to the three main settings of activation and synchronization: fully-synchronous, semi-synchronous, and asynchronous. We establish several results. A main contribution is the constructive proof that asynchronous robots, illuminated with a constant number of colors, are strictly more powerful than traditional semi-synchronous robots.

We also constructively prove that, for luminous robots, the difference between asynchrony and semi-synchrony disappears. This result must be contrasted with the strict dominance between the models without lights (even if the robots are enhanced with an unbounded amount of persistent internal memory).

Additionally we show that there are problems that robots cannot solve without lights, even if they are fully-synchronous, but can be solved by asynchronous luminous robots with $O(1)$ colors. It is still open whether or not asynchronous luminous robots with $O(1)$ colors are more powerful than fully-synchronous robots without lights.

We prove that this is indeed the case if the robots have the additional capability of remembering a single snapshot. This in turn shows that, for asynchronous robots, to have $O(1)$ colors and a single snapshot renders them more powerful than to have an unlimited amount of persistent memory (including snapshots) but no lights.

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1. Introduction

1.1. Framework

Consider a distributed system composed of a team of mobile computational entities, called *robots*, placed in $\mathbb{R}^2$ where they can freely move, each endowed with a personal coordinate system, and operating in *Look–Compute–Move* (LCM) cycles. During a cycle, a robot first obtains a snapshot of the positions of the robots in its own local coordinate system (*Look*); using the snapshot as an input, the robot then executes a protocol, the same for all robots, to compute its destination (*Compute*); finally, moves towards the computed destination, if different from its current location (*Move*). After each cycle, a robot may be inactive for some time. The robots are *autonomous* (i.e., without a central control); they are *silent* (i.e., they have no means of direct communication of information to other robots); and typically they are *oblivious* (i.e., at the beginning of a cycle, a robot has no memory of any observation or computation of its previous cycles). What is computable in such systems has been the object of extensive research within distributed computing. The main goal has been to understand the computational limitations and powers of these robots for performing basic coordination tasks, and the focus has been on basic problems, such as *Pattern Formation* (e.g., [18,20,27,29,31]), *Gathering* (e.g., [1,2,5–7,17,27]), *Flocking* (e.g., [4,21]), *Surrounding* (e.g., [11,12,16]), *Election* (e.g., [13]), etc. For a recent review see [15].

As in other areas of distributed computing, major computational differences exist depending on the level of synchronization of the computational entities. In the literature, three basic settings have been studied: *fully-synchronous* (FSYNC), *semi-synchronous* (SSYNC), and *asynchronous* (ASYNC). In FSYNC, the activations of all robots can be logically divided into global rounds; in each round, the robots are all activated, obtain the same snapshot, compute and perform their move; note that this is computationally equivalent to a fully synchronized system in which all robots are activated simultaneously and all operations are instantaneous. The semi-synchronous model SSYNC is like FSYNC where however not all robots are necessarily activated in each round. In ASYNC, there is no common notion of time, the robots are activated independently, and the duration of each activity and inactivity is finite but unpredictable.

The exploration of the limits of what is computable by such robots is ongoing; the research results obtained so far have greatly increased our basic knowledge and understanding of the relationship between the computability of the three synchronization settings. In particular, there are problems that are solvable in FSYNC but not in SSYNC (e.g. [27]) and, for non-oblivious robots, there are problems that are solvable in SSYNC but not in ASYNC (e.g. [25]); that is, the computational hierarchy (formalized later) between the three settings is strict:

$$\mathrm{FSYNC} > \mathrm{SSYNC} > \mathrm{ASYNC}. \tag{1}$$

Among the basic questions, researchers have been investigating the impact that *additional* robots' capabilities have on the computational power of the system. In particular, a pressing question is what additional power would allow the robots to overcome the inherent difficulties and weaknesses of the ASYNC setting, the weakest one.

In this paper, we analyze the impact of enhancing the computational power of the entities with a simple mechanism for communication and memory. More precisely, each robot is equipped with a constant-sized register (called *light*) whose value (called *color*) is visible to all robots; the lights are persistent, that is, they are not automatically reset at the end of each cycle. Thus, in this new model of *luminous robots*, initially suggested by Peleg [14,24], the entities are capable in each cycle of remembering (because of persistency) and communicating (because of visibility) a constant number of bits. We denote this additional capability of the robots using a superscript representing the number of colors. Thus, ASYNC^i denotes the ASYNC model when each robot is augmented by a light with i colors.

1.2. Main contributions

In this paper, we study the computational relationship between luminous robots and the traditional models of robots without lights, focusing in particular on the impact lights have on asynchrony.

We prove that asynchrony with a constant number of colors is strictly more powerful than traditional semi-synchrony: $\mathrm{ASYNC}^{O(1)} > \mathrm{SSYNC}$. This result is obtained in two steps.

We first prove that, with three bits of externally visible memory, any problem solvable in SSYNC can be solved also in ASYNC. The proof is constructive: we design a ASYNC^5 protocol and prove that, for any given SSYNC protocol $\mathcal{P}$, our protocol produces a semi-synchronous execution of $\mathcal{P}$. We then show that there are problems unsolvable in SSYNC that can however be solved by asynchronous robots augmented with two bits of externally visible memory. Also this proof is constructive: we present a ASYNC^4 protocol that solves the rendezvous of two oblivious robots, a problem that is not solvable in SSYNC.

We also show that, when enhanced with visible lights, the difference between asynchrony and semi-synchrony disappears; in fact we prove that $\mathrm{ASYNC}^{O(1)} \equiv \mathrm{SSYNC}^{O(1)}$. This result must be contrasted with the strict dominance ASYNC < SSYNC in absence of lights (see Expression (1)). Summarizing, we prove that

$$\mathrm{ASYNC}^{O(1)} \equiv \mathrm{SSYNC}^{O(1)} > \mathrm{SSYNC} \tag{2}$$