

Self-organized Multi-robot Task Allocation using Attractive Filed Model: A Taxonomy and Comparison of Centralized and Local Communication

Md Omar Faruque Sarker and Torbjørn S. Dahl

Abstract—This paper proposes to solve multi-robot task-allocation (MRTA) problems using a set of previously published generic rules for self-organised division of labour derived from the observation of ant, human and robotic social systems. The concrete form of these rules, the *attractive filed model* (AFM), are sufficiently abstraction to accommodate different sensing and communication models. We have validated the effectiveness of AFM for MRTA using two bio-inspired communication and sensing strategies: *global sensing - no communication* and *local sensing - local communication*. The former is realized using a centralized communication system and the latter is emulated as a peer-to-peer local communication scheme. Both strategies are evaluated using 16 e-puck robots.

I. INTRODUCTION

MULTI-ROBOT systems can provide high levels of performance, fault-tolerance and robustness in complex and distributed tasks through parallelism and redundancy [1], [2]. *But how can we allocate the tasks among robots?* Traditionally, this issue has been identified as *multi-robot task allocation* (MRTA) [3], analogous to *division of labour* (DOL) in biological and human social systems [4].

MRTA is generally defined as the problem of assigning tasks in an appropriate time to the appropriate robots considering the changes in task-

requirements, team-performance and the environment [5]. The complexities of the *distributed* MRTA problem arise from the fact that there is no central planner or coordinator for task assignments, and in a large multi-robot system, robots are generally limited to local sensing, communication and to interaction.

Within the context of the Engineering and Physical Sciences Research Council (EPSRC) project, 'Defying the Rules: How Self-regulatory Systems Work', we have presented the attractive field model (AFM) [12], a model of self-regulated DOL informed by studies of self-regulated task-allocation in ant and human social systems. AFM suggests four generic rules to explain self-regulation in those social systems. These four rules are: *continuous flow of information*, *concurrency*, *learning* and *forgetting*. All of them are explained below. Primarily, these rules enable the derivation of local control laws for regulating an individual's task-allocation behaviour in a way that facilitates DOL in the entire group.

In biological social systems, communications among the group members, as well as the perception of tasks, are two key components of self-organized DOL. In robotics, existing self-organized task-allocation methods rely heavily upon local sensing and local communication between individuals. AFM however, differs significantly in this point. Being a highly abstract model, it avoids a strong dependence on any specific communication strategy such as the local communications and interactions

M. O. F. Sarker and T. S. Dahl is with Cognitive Robotics Research Centre, University of Wales, Newport, Newport Business School, Allt-yr-yn Campus Newport, NP20 5DA, United Kingdom. e-mail: Mdomarfaruque.Sarker@newport.ac.uk

found in many existing approaches to MRTA. AFM uses the abstraction of attractive fields or continuous flows of information from tasks to agents. This flow of information can be realized by through either centralized or decentralized communication strategies under explicit and implicit communication modes.

In order to enable continuous flow of information in our multi-robot system, we have implemented two types of sensing and communication strategies inspired by the self-regulated DOL found in two types of social wasps: *polistes* and *polybia* [13]. Depending on the group size, these species follow different strategies for communication and sensing of tasks. Polistes wasps are called *independent founders*. In this species reproductive females establish colonies alone or in small groups (in the order of 10^2), but independent of any sterile workers. Polybia wasps, on the other hand, are called *swarm founders* where a swarm of workers and queens initiate colonies consisting of several hundreds to millions of individuals.

The most notable difference in the organization of work in these two social wasps is that independent founders do not rely on any cooperative task performance while swarm founders interact with each other locally to accomplish their tasks. The work mode of independent founders can be considered as *global sensing - no communication (GSNC)* where the individuals sense the task requirements throughout a small colony and do these tasks without communicating with each other. The work mode of the swarm founders, on the other hand, can be treated as *local sensing - local communication (LSLC)* where the individuals can only sense tasks locally due to the large colony size and can communicate locally to exchange information, e.g. task-requirements (although their exact communication mechanism is unknown). In the study presented here, we have compared the performance of these two sensing and communication strategies for self-regulated DOL in robots under AFM.

The main contributions of this paper are as follows. This study compares the performance of two bio-inspired sensing and communication strategies in producing self-regulated MRTA. A flexible multi-

robot control architecture has been developed adopting D-Bus inter-process communication technology. A novel taxonomy of MRTA solutions has been derived based on organization of task-allocation, interaction and communication.

This paper has been organized as follows. Section 2 reviews the related literature on MRTA. Section 3 presents the new taxonomy of MRTA solutions. Section 4 presents AFM based task-allocation solution for multi-robot systems. Section 5 describes our centralized and local communication schemes used in this study. Section 6 and Section 7 present the design and implementation of our experiments respectively. Section 8 describes our results. Section 9 discusses the performance of self-regulated MRTA under both centralized and local communication strategies. Section 10 draws conclusions and presents possibilities for future work.

II. RELATED WORK

Since the 90s, many robot control architectures have been designed with the sole purpose of addressing the MRTA issue from different perspectives. Based on the high-level design of those solutions, we have classified them into two categories: i) *predefined or explicit* task-allocation and ii) *bio-inspired self-organized* task-allocation.

Early research on explicit task-allocation was dominated by explicit cooperation [6], use of dynamic role assignment [7] and market-based bidding approach [8]. When taking these approaches, robots perform explicit task-allocation activities, commonly including communication with other group members for negotiating tasks. These approaches are intuitive and comparatively straightforward to design and implement and can be analysed formally. However, these approaches typically work well only when the number of robots are small (≤ 10) [9].

Task performance in self-organized approaches relies on the collective behaviours resulting from the local interactions of many simple and mostly homogeneous or interchangeable agents. Robots choose their tasks independently using general principles of self-organization such as: positive and negative

feedback, multiple interactions among entities and their environment, and randomness or amplification of fluctuations [20]. Moreover, interaction among individuals and their environment can be modulated by stigmergic, local and global communications. Among many variants of self-organized task-allocation mechanisms, the most common type is threshold-based task-allocation [21]. In this approach, a robot's decision to select a particular task depends largely on its perception of a stimulus, e.g., the demand for a task to be performed, and its corresponding response threshold for that task.

Under the deterministic response-threshold approach, each robot has an activation threshold for each task that needs to be performed. It continuously perceives or monitors the stimulus of all tasks that reflect the relative urgencies of tasks. When a particular task-stimulus exceeds a predefined threshold the robot starts working on that task, typically reducing the related stimuli. When the task-stimuli falls below the fixed threshold the robot abandons that task. This type of approach has been effectively applied in foraging [11], [22] and aggregation [23]. The fixed response threshold can initially be same for all robots [24] or they can be different according to robot capabilities or the configuration of the system [22]. Adaptive response-threshold models change the thresholds over time. A robot's response threshold for a given task is often decreased as a result of the robot performing that task. This enables a robot to select that particular task more frequently or in other words specialise on that task [21], [23].

Unlike the deterministic approach, where robots respond predictably, e.g., to the task stimulus that is the furthest above its threshold, probabilistic or stochastic approaches offer a selection process based on a probability distribution over the tasks. In this case, all tasks commonly have at least a small, non-zero probability of being chosen. This random element typically prevents starvation of low-stimulus tasks.

Bio-inspired, self-organized MRTA mechanisms rely to a much smaller degree on modelling the environment, tasks or robot capabilities. Most existing research in this area considers a single global task

e.g. foraging, area cleaning and box-pushing with the focus of the work being the design of individual robot controllers that can accomplish the task [5]. More research is needed to study the performance of the self-organized approach in handling several different tasks.

Both of the above task-allocation approaches expose their relative strengths and weaknesses when they are put under real-time experiments with variable number of robots and tasks. In an arbitrary event handling domain, a comparison between self-organized and predefined market-based task-allocation was reported by Kalra and Martinoli [25]. They found that explicit task-allocation was more efficient when the required information could be captured accurately. The threshold-based approach offered similar quality of allocation at a fraction of cost in noisy environment.

Gerkey and Mataric have presented a study [5] that compared the complexity and performance of key architectures, including ALLIANCE [14], the Broadcast of local eligibility (BLE) architecture [26], M+ [27], MURDOCH [28], First piece auctions [29] and Dynamic role assignment [7]. All of these rely on explicit task-allocation mechanisms. The computational and communication requirements of these MRTA systems were expressed as a function of the number of robots and tasks. Although the study did not explicitly measure the scalability of the architectures, it clearly showed that many explicit task-allocation mechanisms fail to scale well in environments where the number of robots and tasks are large, given limited overall communication bandwidth and limited processing power for individual robots.

III. A TAXONOMY OF MRTA

In order to understand the interplay among task-allocation, communication and interaction of a particular MRTA approach we have presented these aspects in two 2D characteristic plots. From this classification we can get an insight about the complexities involved in various kinds of MRTA problems and the design choices involved in them. Fig. 1 presents the classification of MRTA solutions based on task-allocation and communication strategies

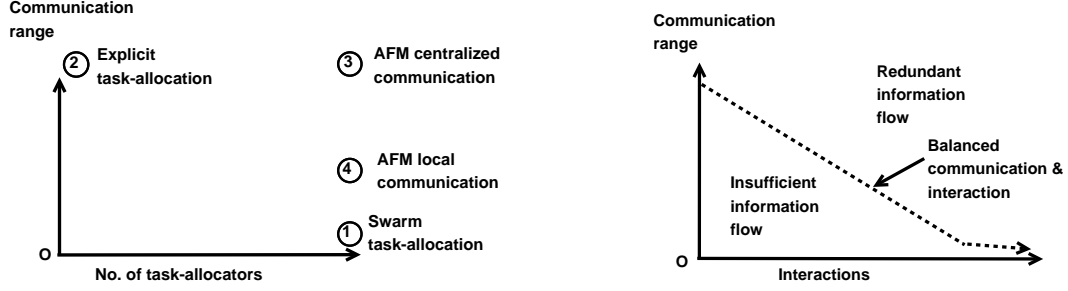


Fig. 1: Classification of MRTA solutions based on task-allocation and communication strategies

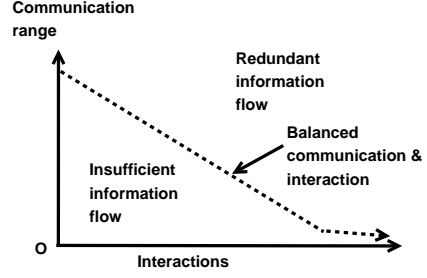


Fig. 2: Information flow caused by different levels of communication and interaction

used to disseminate information. Here horizontal axis shows the number of active nodes that provides the task-allocation to the group. The origin of this axis represents the explicit task-allocation by a single centralized entity. For example, in any explicit task-allocation approach, we can use one external centralized entity or one of the robots (aka *leader*) to manage the task-allocation. In many predefined methods, e.g. in market-based systems, multiple nodes can act as mediators or task-allocators. Under predefined task-allocation approach, a small number of robots can have fully distributed task-allocation where each robot acts as an independent task-allocator (e.g. as in ALLIANCE architecture). The right extreme of horizontal axis in Fig. 1 represents the swarm task-allocation method which is fully distributed, i.e. each robot selects its tasks independently and without the help of a leader. However, robots might be dependent on other entities for getting the latest *information* about tasks. In a recent study on swarm-robotic flocking, [30] show that a swarm can be guided to a target by a few informed individuals or leaders while the remaining robots remain self-organized. Task-allocation in a swarm of robots through one central entity may be rare since one of the major motivations behind swarm robotic systems is to make the swarm task-allocation more robust by avoiding single point of failure. The vertical axis in Fig. 1 shows the communication

range of individual entities. In case of implicit communication via stigmergy in swarm task-allocation this range does not exist. On the other hand, in case of explicit task-allocation a global range can cover all entities. In this research we have placed our two kinds of experiments vertically aligned with swarm task-allocation. AFM centralized communication represents a GSNC system where communication range is global and task-allocation is fully distributed. Similarly, AFM local communication also represents the fully distributed task-allocation but with limited communication range under LSLC strategy.

The information flow caused by different levels of communication and interaction has been depicted in Fig. 2. This group-level interaction can be classified into four types: *collective*, *cooperative*, *coordinative* and *collaborative* [6]. From this plot we can see two extremes of information flow. Insufficient information flow occurs when individual's communication range is low and their interaction is limited. In such cases, system designed can find suitable trade-off to get a balanced information flow by increasing communication range or interaction frequency or both. On another extreme of this situation we can find lot of redundant information flow where all individuals are both communicating and interacting. Thus the dotted line in the plot refers to a balanced communication and interaction.

This dotted line does not completely intersect the horizontal line since when the communication range is limited to the next neighbour, individuals can still continue to interact with others as much as possible.

The presence of interaction can be due to the nature of the problem, e.g. cooperation is necessary in co-operative transport tasks. Alternately, this interaction can be a design choice where interaction can improve the performance of the team, e.g. cooperation in cleaning a work-site is not necessary but it can help to improve the efficiency of this task. This plot can also be used to refer to the degree of coupling present in the system. In case of collective interaction, robots merely co-exist, i.e. they may not be aware of each other except treating others as obstacles. Many multi-robot systems are loosely-coupled where robots can indirectly infer some states of the environment from their team-mates' actions. But in many cases, e.g. in co-operative transport, robots not only recognize others as their team-mates, but also they coordinate their actions. Thus they form a tightly coupled system. This level of interaction and coupling also gives us the information about potential side-effects of failure of an individual robot. Tightly coupled systems with high degrees of interactions among the robots suffer from the performance loss if some of the robots removed from the system.

The communication overhead can be resulted from the interactions of robots under a given task-allocation method. Various task-allocation methods rely upon variable degrees of robot-robot communications. On the other hand, the communication capabilities of individual robots can limit (or expand) the level of interaction can be made in a given group. Thus in one way, considering the interaction requirements of a MRTA problem, the system designer can select suitable communication strategies that both minimizes the communication overhead and maximizes the performance of the group. And in other way, the communication capabilities of robots can guide a system designer to design interaction rules of robot teams, e.g. the specification of robot's on-board camera can determine the degree of possible visual interactions among robots. The suitable trade-off between these

two axes: communication range and interaction can give us a balanced design of our MRTA solution.

IV. MULTI-ROBOT TASK-ALLOCATION USING AFM

A. Attractive Field Model

The probability of an agent choosing to perform a task is proportional to the strength of the task's attractive field, as given by Equation 1.

$$P_j^i = \frac{S_j^i}{\sum_{j=0}^J S_j^i} \text{ where, } S_0^i = S_{RW}^i \quad (1)$$

Equation 1 states that the probability of an agent, i , selecting a task, j , is proportional to the stimulus, S_j^i , perceived from that task, with the sum of all the task stimuli normalised to 1.

The strength of an attractive field varies according to how sensitive the agent is to that task, k_j^i , the distance between the task and the agent, d_{ij} , and the *urgency*, ϕ_j of the task. In order to give a clear edge to each field, its value is modulated by the hyperbolic tangent function, \tanh . Equation 2 formalises this part of AFM.

$$S_j^i = \tanh\left\{\frac{k_j^i}{d_{ij} + \delta}\phi_j\right\} \quad (2)$$

Equation 2, used small constant δ , called *delta distance*, to avoid division by zero, in the case when a robot has reached to a task.

Equation 3 shows how AFM handles the the no-task, or random walk, option. The strength of the stimuli of the random walk task depends on the strengths of the fields real tasks. In particular, when the other tasks have a low overall level of sensitisation, i.e., relatively weak fields, the strength of the random walk field is relatively high. On the other hand, when the agent is highly sensitised, the strength of the random walk field becomes relatively low. We use J to denote the number of real tasks. AFM effectively considers random walking as an ever present additional task. Thus the total number of tasks becomes $J + 1$.

$$S_{RW}^i = \tanh\left\{1 - \frac{\sum_{j=1}^J S_j^i}{J + 1}\right\} \quad (3)$$

A task j has an associated urgency ϕ_j indicating its relative importance over time. If an agent attends a task j in time step t , the value of ϕ_j will decrease by an amount $\delta_{\phi_{DEC}}$ in the time-step $t + 1$. On the other hand, if a task has not been served by any of the agents in time-step t , ϕ_j will increase by a different amount, $\delta_{\phi_{INC}}$ in time-step $t + 1$. This behaviour is formalised in Equations 4 and 5.

$$\text{If the task is not being done: } \phi_{j,t+1} \rightarrow \phi_{j,t} + \delta_{\phi_{INC}} \quad (4)$$

$$\text{If the task is being done: } \phi_{j,t+1} \rightarrow \phi_{j,t} - n \delta_{\phi_{DEC}} \quad (5)$$

Equation 4 refers to a case where no agent attends to task j and Equation 5 to the case where n agents are concurrently performing task j .

In order to complete a task, an agent needs to be within a fixed distance of that task. When an agent performs a task, it learns about it and this will increase the probability of that agent selecting that task in the future. This is done by increasing its sensitization to the task by a fixed amount, k_{INC} . The variable affinity of an agent, i , to a task, j , is called its *sensitization* to that task and is denoted k_j^i . If an agent, i , does not do a task j , k_j^i is decreased by a different fixed amount, k_{DEC} . This behaviour is formalised in Equations 6 and 7.

$$\text{If task is done: } k_j^i \rightarrow k_j^i + k_{INC} \quad (6)$$

$$\text{If task is not done: } k_j^i \rightarrow k_j^i - k_{DEC} \quad (7)$$

Each robot is modelled as an agent and each task is modelled as a spatial location. The robots repeatedly select tasks and if the robot is outside a fixed task boundary, it navigates towards the task. If the robot is within the task boundary it remains there until the end of the time step when a new (or the same) task is selected. The distance between a task and a robot is simply the physical distance and the sensitivities are recorded as specific values on each robot. The urgency values of the tasks are calculated based on the number of robots attending each task and the updated urgency values are communicated to the robots.

The sensing of the distance between the tasks and robots as well as the communication of urgency values are non-trivial in a robotic system. Both

the sensing and communication can be done either locally by the individual robots or centrally, through an overhead camera and a global communication network. This article presents work on exploring the effects of different sensing and communication models on the performance of MRTA systems.

We have designed a set of manufacturing shop-floor scenario experiments for validating the effectiveness of our AFM in producing self-regulated MRTA. In this section, we have described our manufacturing shop-floor scenario and our task-allocation solution for robot-controllers.

B. A manufacturing shop-floor scenario

By extending our interpretation of AFM in multi-robot system, we can set-up manufacturing shop-floor scenario. Here, each task represents a manufacturing machine that is capable of producing goods from raw materials, but they also require constant maintenance works for stable operations. Let W_j be a finite number of material parts that can be loaded into a machine j in the beginning of its production process and in each time-step, ω_j units of material parts can be processed ($\omega_j \ll W_j$). So let Ω_j^p be the initial production workload of j which is simply: W_j/ω_j unit.

We assume that all machines are identical. In each time step, each machine always requires a minimum threshold number of robots, called hereafter as *minimum robots per machine* (μ), to meet its constant maintenance work-load, Ω_j^m unit. However, if μ or more robots are present in a machine for production purpose, we assume that, no extra robot is required to do its maintenance work separately. These robots, along with their production jobs, can do necessary maintenance works concurrently. For the sake of simplicity, here we consider $\mu = 1$.

Now let us fit the above production and maintenance work-loads and task performance of robots into a unit task-urgency scale. Let us divide our manufacturing operation into two subsequent stages: 1) *production and maintenance mode* (PMM), and 2) *maintenance only mode* (MOM). Initially a machine starts working in PMM and does production and maintenance works concurrently. When there is no production work left, then it enters

into MOM. Fig. ?? illustrates this scenario for a single machine.

Under both modes, let α_j be the amount of workload occurs in a unit time-step if no robot serves a task and it corresponds to a fixed task-urgency $\Delta\phi_{INC}$. On the other hand, let us assume that in each time-step, a robot, i , can decrease a constant workload β_i by doing some maintenance work along with doing any available production work. This corresponds to a negative task urgency: $-\Delta\phi_{DEC}$. So, at the beginning of production process, task-urgency, occurred in a machine due to its production work-loads, can be encoded by Eq. 8.

$$\Phi_{j,INIT}^{PMM} = \Omega_j^p \times \Delta\phi_{INC} + \phi_j^{m0} \quad (8)$$

where ϕ_j^{m0} represents the task-urgency due to any initial maintenance work-load of j . Now if no robot attends to serve a machine, each time-step a constant maintenance workload of α_j^m will be added to j and that will increase its task-urgency by $\Delta\phi_{INC}$. So, if k time steps passes without any production work being done, task urgency at k^{th} time-step will follow Eq. 9.

$$\Phi_{j,k}^{PMM} = \Phi_{j,INIT}^{PMM} + k \times \Delta\phi_{INC} \quad (9)$$

However, if a robot attends to a machine and does some production works from it, there would be no extra maintenance work as we have assumed that $\mu = 1$. Rather, the task-urgency on this machine will decrease by $\Delta\phi_{DEC}$ amount. If ν_k robots work on a machine simultaneously at time-step k , this decrease will be: $\nu_k \times \Delta\phi_{DEC}$. So in such cases, task-urgency in $(k + 1)^{th}$ time-step can be represented by:

$$\Phi_{j,k+1}^{PMM} = \Phi_{j,k}^{PMM} - \nu_k \times \Delta\phi_{DEC} \quad (10)$$

At a particular machine j , once $\Phi_{j,k}^{PMM}$ reaches to zero, we can say that there is no more production work left and this time-step k can give us the *production completion time* of j , T_j^{PMM} . Average production time-steps of a shop-floor with M machines can be calculated by the following simple equation.

$$T_{avg}^{PMM} = \frac{1}{M} \sum_{j=1}^M T_j^{PMM} \quad (11)$$

T_{avg}^{PMM} can be compared with the minimum number of time-steps necessary to finish production works, T_{min}^{PMM} . This can only happen in an ideal case where all robots work for production without any random walking or failure. We can get T_{min}^{PMM} from the total amount of work load and maximum possible inputs from all robots. If there are M machines and N robots, each machine has Φ_{INIT}^{PMM} task-urgency, and each time-step robots can decrease $N \times \Delta\phi_{DEC}$ task-urgencies, then the theoretical T_{min}^{PMM} can be found from the following Eq. 12.

$$T_{min}^{PMM} = \frac{M \times \Phi_{INIT}^{PMM}}{N \times \Delta\phi_{DEC}} \quad (12)$$

$$\zeta_{avg}^{PMM} = \frac{T_{avg}^{PMM} - T_{min}^{PMM}}{T_{min}^{PMM}} \quad (13)$$

Thus we can define ζ_{avg}^{PMM} , average production completion delay (APCD) by following Eq. 13: When a machine enters into MOM, only μ robots are required to do its maintenance works in each time step. So, in such cases, if no robot serves a machine, the growth of task-urgency will follow Eq. 9. However, if ν_k robots are serving this machine at a particular time-step k^{th} , task-urgency at $(k + 1)^{th}$ time-step can be represented by:

$$\Phi_{j,k+1}^{MOM} = \Phi_{j,k}^{MOM} - (\nu_k - \mu) \times \Delta\phi_{DEC} \quad (14)$$

By considering $\mu = 1$, Eq. 14 will reduces to Eq. 10. Here, $\Phi_{j,k+1}^{MOM}$ will correspond to the *pending maintenance work-load* of a particular machine at a given time. This happens due to the random task switching of robots with a no-task option (random-walking). Interestingly PMW will indicate the robustness of this system since higher PMW value will indicate the delay in attending maintenance works by robots. We can find the *average pending maintenance work-load* (APMW) per time-step per machine, χ_j^{MOM} (Eq. 15) and average PMW per machine per time-step, χ_{avg}^{MOM} (Eq. 16).

$$\chi_j^{MOM} = \frac{1}{K} \sum_{k=1}^K \Phi_{j,k}^{MOM} \quad (15)$$

$$\chi_{avg}^{MOM} = \frac{1}{M} \sum_{j=1}^M \chi_j^{MOM} \quad (16)$$

C. Robot-controller algorithms

In our task-allocation algorithm, for each task, we extract its pose, urgency, sensitisation from input data. *CalculateTaskDistance()* function calculates the Euclidian distance between a task and a the robot by taking the current robot-pose and static task-pose as the input. These values are enough to get a task's stimuli based on Eq. 2. We get the random-walk task's stimuli from Eq. 3.

Algorithm 1: Self-regulated task-allocation by AFM

```

1: Input: AllTaskInfo, RobotPose, TaskRecords, DeltaDistance
2: Output: SelectedTaskID
3: comment: Stage 1: Get sum of stimulus of all tasks
4: TotalTasks  $\leftarrow$  Total number of tasks  $\in$  AllTaskInfo
5: TaskStimuliSum  $\leftarrow$  0
6: for all Task  $\in$  AllTaskInfo do
7:   TaskPose  $\leftarrow$  Task-position  $\in$  Task
8:   TaskUrgency  $\leftarrow$  Task-urgency  $\in$  Task
9:   TaskSensitization  $\leftarrow$  Task-sensitization  $\in$  Task
10:  DistToTask  $\leftarrow$  CalculateTaskDistance(RobotPose, TaskPose)
11:  TaskStimuli  $\leftarrow$  CalculateTaskStimuli(DistToTask, TaskSensitization, TaskUrgency, DeltaDistance)
12:  TaskStimuliSum  $\leftarrow$  TaskStimuliSum + TaskStimuli
13:  TaskRecords  $\leftarrow$  UpdateTaskRecords(TaskStimuli, DistToTask, TaskUrgency, TaskSensitization)
14: end for
15: RandomWalkStimuli  $\leftarrow$  CalculateRandomWalkStimuli(TotalTasks, TaskStimuliSum)
16: AllStimuliSum  $\leftarrow$  TaskStimuliSum + RandomWalkStimuli
17: comment: Stage 2: Find probability of doing each task
18: TaskID  $\leftarrow$  0
19: while TaskID  $\leq$  TotalTasks do
20:   TaskStimuli  $\leftarrow$  Task-stimuli  $\in$  TaskRecords(TaskID)
21:   TaskProbability  $\leftarrow$  GetTaskProbability(TaskStimuli, AllStimuliSum)
22:   TaskProbabilityRange  $\leftarrow$  ConvertTaskProbabilityIntoRange(TaskProbability)
23:   TaskRecords  $\leftarrow$  UpdateTaskRecords(TaskRecords, TaskProbability)
24: end while
25: comment: Stage 3: Draw a random-number to match TaskID

```

```

31: RandomNum  $\leftarrow$  GetRandomNumber(0, Max(TaskProbabilityRange))
32: while TaskID  $\leq$  TotalTasks do
33:   RangeStart  $\leftarrow$  Min(TaskProbabilityRange(TaskID))
34:   RangeEnd  $\leftarrow$  Max(TaskProbabilityRange(TaskID))
35:   if RandomNum  $\geq$  RangeStart && RandomNum  $\leq$  RangeEnd then
36:     SelectedTaskID  $\leftarrow$  TaskID
37:   end if
38: end while

```

In the second stage of our task-allocation algorithm, we find the probability of each task (including random-walk) based on Eq. 1. Then this probability value of each task, between 0 and 1, is rounded to the closest two-digit fractions and multiplied by 100 and put into a linear scale. Then we use a random-number generator that draws a random-number between 0 and the highest value of task-probability range. Then this random number is compared against the task probability range of each task. Under this probabilistic method, the task with larger probability range has a higher chance to be selected, but low probability tasks can also be selected time-to-time.

Algorithm 2: Robot's learning and forgetting of tasks

```

1: Input: TaskRecords, LeranRate, ForgetRate, SelectedTaskID
2: Output: Updated TaskSensitisation  $\in$  TaskRecords
3: for all Task  $\in$  TaskRecords do
4:   TaskID  $\leftarrow$  ID  $\in$  Task
5:   TaskSensitization  $\leftarrow$  Sensitisation  $\in$  Task
6:   if TaskID  $\equiv$  SelectedTaskID then
7:     TaskSensitization  $\leftarrow$  Max(1, (TaskSensitization + LeanRate))
8:   else
9:     TaskSensitization  $\leftarrow$  Min(0, (TaskSensitization - ForgetRate))
10:   end if
11: end for

```

Algorithm 2 lists the pseudo-code for updating (learning and forgetting) the robot's task-sensitization values. Along with previously mentioned *TaskID*, *TaskRecords*, and *SelectedTaskID*, it takes

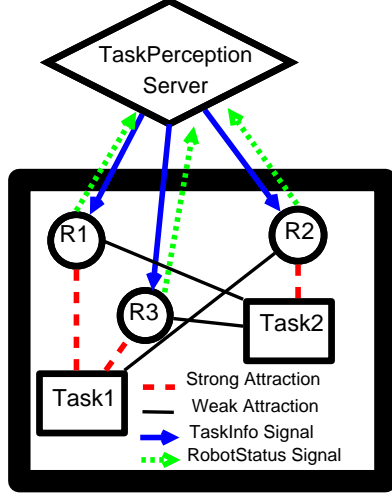


Fig. 3: A centralized communication scheme

two other inputs: *LeranRate* (Δk_{INC}) and *ForgetRate* (Δk_{DEC}) as outlined in Eq. 6 and 7 respectively. In addition to that it also keep the value of task-sensitization between the fixed limit of 0 and 1.

V. COMMUNICATION MODELS

A. Centralized communication model

AFM relies upon a system-wide continuous flow of information which can be realized using any suitable communication model. A simple centralized communication scheme is outlined in Fig. 3. In this model we have used bi-directional signal-based exchange of communication messages between a centralized *task perception server* (TPS) and a *robot-controller client* (RCC). The main role of TPS is to send up-to-date task-information to RCCs. This task-information mainly contains the location and urgency of all tasks which is used by the RCCs for running their task-allocation algorithm. The urgency value of each task is dynamically updated by TPS after receiving the status signals from the working robots of that particular task. Fig. 3 shows how three robots are attracted to two different tasks and their communications with TPS. Here although the robots are selecting task independently based-on the strength of their attractive fields to different tasks,

they are depended on the TPS for task-information. AFM suggests the communication of task-urgencies among robots. This communication helps the robots to gain information that can be treated as “global sensing”. However in this model robots do not communicate among themselves. Hence this model can be approximated as the GSNC strategy. Since in order to run the task-allocation algorithm robot-controllers need the distance information we also include the task position information in the message. Our centralized communication model is open to include any further information, such as timestamp, in the message payload. In this centralized communication model the frequency of signal emission depends on several issues, e.g. the rate at which the environment is changing, the bandwidth of communication medium. In case of time-extended tasks, robots can receive information less frequently and the bandwidth usage can be kept minimum. However under a fast changing environment relatively more bandwidth will be required. Finally the centralized communication model spread the attractive fields of all tasks globally by broadcasting information to all robots.

The algorithm that updates the task-urgencies in TPS is given here.

Algorithm 3: Task-urgency update rules based on AFM

```

1: Input: AllTaskInfo, AllTaskWorkers, ThresholdWorkers,
2:   DeltaUrgencyINC, DeltaUrgencyDEC
3: Output: Updated TaskUrgencies  $\in$ 
   AllTaskInfo
4: for all (Task, Workers)  $\in$ 
   (AllTaskInfo, AllTaskWorkers) do
5:   TaskUrgency  $\leftarrow$  Task-urgency  $\in$  Task
6:   TaskWorkers  $\leftarrow$  Number of workers  $\in$ 
   Workers
7:   if TaskWorkers < ThresholdWorkers then
8:     TaskUrgency  $\leftarrow$ 
       Max(1, (TaskUrgency + DeltaUrgencyINC))
9:   else
10:    TaskUrgency  $\leftarrow$  Min(0, (TaskUrgency -
11:      DeltaUrgencyDEC))
12:   end if
13: end for

```

The above algorithm relies on the previously mentioned task-status signals from the working robots.

It sorts out the worker robots' robot-id according to their task-id and use the worker count to determine whether the corresponding task-urgency needs any change according the rules of AFM. For example, here we have shown that if the number of working robots exceeds a pre-set threshold task urgency has been updated based on Eq. 4 and 5. Moreover, in order to satisfy our interpretation of AFM, the task-urgency values are kept within a fixed range 0 and 1.

B. Local P2P communication model (LPCM)

In most swarm robotic research local communication is considered as the one of the most critical components of the swarms where the global behaviours emerges from the local interactions among the individuals and their environment. In this study, we have used the concepts of pheromone active-space of ants to realize our simple LSLC scheme. Ants use various chemical pheromones with different active spaces (or communication ranges) to communicate different messages with their group members [32]. Ants sitting near the source of this pheromone sense and respond quicker than others who wander in far distances. Thus both communication and sensing occurs within a small communication range¹. We have used this concept of communication range or locality in our LPCM. A suitable range (or radius) of communication and sensing can be set at design time based on the capabilities of robots [23]. Alternately they can also be varied dynamically over time depending on the cost of communication and sensing, e.g. density of peers, ambient noise in the communication channels, or even by aiming for maximizing information spread [33]. In this study, we have followed the former approach as our robots do not have the precise hardware to dynamically vary their communication and sensing ranges. Below we describe the general characteristics and implementation algorithm and strategy of LPCM. Our LPCM relies on

¹Although, generally communication and sensing are two different issues, however within the context of our self-regulated MRTA, we have broadly viewed sensing as the part of communication process, either implicitly via environment, or explicitly via local peers.

the local P2P communications among robots. we have assumed that robots can communicate to its nearby peers within a certain communication radius, r_{comm} and they can sense tasks within another radius r_{task} . They exchange communication signals reliably without any significant loss of information. A robot R_1 is a *peer* of robot R_2 , if spatial distance between R_1 and R_2 is less than this r_{comm} . Similarly, when a robot comes within this r_{task} of a task, it can sense the status of this task. Although the communication and sensing range can be different based on robot capabilities, we have considered them same for the sake of simplicity of our implementation.

Local communication can also give robots similar task information as in centralized communication. In this case, it is not necessary for each robot to communicate with every other robot to get information on all tasks. Since robots can random walk and explore the environment we assume that for a reasonably high robot-to-space density, all tasks will be known to all robots after an initial exploration period. In order to update the urgency of a task, robots can estimate the number of robots working on a task in two ways: by either using their sensory perception (e.g. on-board camera) or doing local P2P communication with others.

Similar to our centralized communication model, we can characterize our local communication model in terms of message content, communication frequency and target recipients [31]. Regarding the issue of message content, our local communication model is open. Robots can communicate with their peers with any kind of message. Our local model addresses the last two issues very specifically. Robots communicate only when they meet their peers within a certain communication radius (r_{comm}). Although in case of an environment where robots move relatively faster the peer relationships can also be changed dynamically. But this can be manipulated by setting the signal frequency and robot to space density to somewhat reasonably higher value.

In terms of target recipients, our model differs from a traditional publish/subscribe communication model by introducing the concept of dynamic sub-

scription. In a traditional publish/subscribe communication model, subscription of messages happens prior to the actual message transmission. In that case prior knowledge about the subjects of a system is necessary. But in our model this is not necessary as long as all robots use a common addressing convention for naming their incoming signal channels. In this way, when a robot meets with another robot it can infer the address of this peer robot's channel name by using a shared rule. A robot is thus always listening to its own channel for receiving messages from its potential peers or message publishers. On the other side, upon recognizing a peer, a robot sends a message to this particular peer. So here neither it is necessary to create any custom subject name-space [31] nor we need to hard-code information in each robot controller about the knowledge of their potential peers *a priori*. **Algorithm 4: Locality based P2P Communication Model**

```

1: Input:  $RobotID, r_{comm}, r_{task}, TaskInfoDB, RobotPose$ 
2:    $ListeningBuffer, EmissionBuffer$ 
3: Output: updated  $TaskInfoDB$ 
4: comment: Perception of a task, if the robot is within  $r_{task}$ 
5:  $TaskPose \leftarrow$  Estimate/get pose of a task within  $r_{task}$ 
6:  $TaskUrgency \leftarrow$  Estimate/get urgency of a task within  $r_{task}$ 
7:  $TaskInfo \leftarrow (TaskPose, TaskUrgency)$ 
8:  $TaskInfoDB \leftarrow$ 
    $UpdateTaskInfoDB(TaskInfo)$ 
9: comment: Listening  $LocalTaskInfo$  signal(s) from peers
10:  $RobotPeers \leftarrow$  Identify/get a list of peers within  $r_{comm}$ 
11: for all  $peer \in RobotPeers$  do
12:   if (caught a  $LocalTaskInfo$  signal from nearby peer) then
13:      $ListeningBuffer \leftarrow LocalTaskInfo$  of peer
14:    $TaskInfoDB \leftarrow$ 
      $UpdateTaskInfoDB(ListeningBuffer)$ 
15:   end if
16: end for
17: comment: Emitting own  $LocalTaskInfo$  signal to peers
18:  $EmissionBuffer \leftarrow TaskInfoDB$ 
19: for all  $peer \in RobotPeers$  do

```

```

20:   EmitLocalTaskInfoSignal(peer,
      $EmissionBuffer$ )
21: end for
22:  $RobotPeers \leftarrow 0$ 

```

Within the context of our self-regulated MRTA experiments under AFM, we have formalized the following three aspects of LPCM into an implementation algorithm.

- 1) Sensing the presence of the local peers and task, if any.
- 2) Listening to the task-information signals from local peers.
- 3) Emitting local task-information signals to local peers.

From Algorithm 4, we see that a robot controller is initialized with its specific $RobotID$ and default values of r_{comm} and r_{task} that correspond to the robot's communication and sensing ranges respectively. We have assumed that these values are same for all robots and for all tasks. Initially a robot has no information about tasks, i.e. $TaskInfoDB$, $ListeningBuffer$ and $EmissionBuffer$ all are empty. Upon sensing a task, robot determines the task's pose and urgency of that task. This is not strictly necessary as this information can also be available from alternate sources, e.g. via communicating with a TPS which is discussed later.

Robot controller then executes the **UpdateTaskInfoDB()** that modified the robot's information about the corresponding task. In second step, robot senses its nearby peers located within r_{comm} . The potential $LocalTaskInfo$ signal reception from a peer again triggers the **UpdateTaskInfoDB()** function. In the last step, robot emits its own task information as a $LocalTaskInfo$ signal to its peers.

VI. EXPERIMENTAL DESIGN

The overall aim of our MRTA experiments is to compare the various properties of self-regulated MRTA under both GSNC and LSLC strategies. These experiments are grouped into four series labeled using the following letters: A, B, C and D. Series A and B experiments are done using a centralized communication system under GSNC strategy and Series C and D experiments are carried

TABLE I: Experimental parameters of Series A & B experiments

Parameter	Series A	Series B
Total number of robots (N)	8	16
Total number of tasks (M)	2	4
Experiment area (A)	2 m^2	4 m^2
Initial production work load/machine (Ω_j^P)	100 unit	
Task urgency increase rate ($\Delta\phi_{INC}$)	0.005	
Task urgency decrease rate ($\Delta\phi_{DEC}$)	0.0025	
Initial sensitization (K_{INIT})	0.1	
Sensitization increase rate (Δk_{INC})	0.03	
Sensitization decrease rate (Δk_{DEC})	0.01	

out using an emulated local P2P communication under LSLC strategy. Below we describe the observables, parameters and implementation of our experiments.

A. Observables

Thus, in order to observe the above properties of self-regulated MRTA, we have designed our experiments to record the following observables in each time-step.

- 1) Task-urgency of each task (ϕ).
- 2) Number of robots engaged in each task.
- 3) Task-sensitizations (k) of robots.
- 4) Pose data of robots.
- 5) Communication of task-information message among TPS and RCCs.

B. Parameters

Table I lists a set of essential parameters of our GSNC strategy based experiments (Series A and B). We intend to have a set-up that is relatively complex, i.e., with a high number of robots and tasks in a large area. The diameter of the marker of our e-puck robot is 0.08m. So, if we put 4 robots in an area of one square meter, this will give us a robot-occupied-space to free-space ratio of about 1:49 per square meter. This ratio is reasonable in order to allow the robots to move at a speed of 5

cm/sec without causing much interference to each other.

The initial values of task urgencies correspond to 100 units of production work-load without any maintenance work-load as outlined in Eq. 8. We choose a limit of 0 and 1, where 0 means no urgency and 1 means maximum urgency. Same rule applies to sensitization, where 0 means no sensitization and 1 means maximum sensitization. This also implies that if sensitization is 0, task has been forgotten completely. On the other hand, if sensitization is 1, the task has been learnt completely. We choose a initial sensitization value of 0.1 for all tasks. The following relationships are maintained for selecting task-urgency and sensitization parameters.

$$\Delta\phi_{INC} = \frac{\Delta\phi_{DEC} \times N}{2 \times M} \quad (17)$$

$$\Delta k_{DEC} = \frac{\Delta k_{INC}}{M - 1} \quad (18)$$

Eq. 17 establishes the fact that task urgency will increase at a higher rate than that of its decrease. As we do not like to keep a task left unattended for a long time we choose a higher rate of increase of task urgency. This difference is set on the basis of our assumption that at least half of the expected number of robots (ratio of number of robots to tasks) would be available to work on a task. So they would produce similar types of increase and decrease behaviours in task urgencies.

Eq. 18 suggests that the learning will happen much faster than the forgetting. The difference in these two rates is based on the fact that faster learning gives a robot more chances to select a task in next time-step and thus it becomes more specialized on it.

Our LSLC strategy based experiments (Series C and D) follow the similar design of experimental parameters and observables of Series B experiments as outlined above. Table II highlights the major parameters of these experiments. For the sake of simplicity, the communication and sensing range values are kept same in both series of experiments. Series D uses larger ranges that enables our robot to capture more task information at a time. That is

TABLE II: Experimental parameters of Series C & D experiments

Parameter	Series C	Series D
task-perception range (r_{task})	$0.5m$	$1m$
Communication range (r_{comm})	$0.5m$	$1m$
Total number of robots (N)	16	
Total number of tasks (M)	4	
Experiment area (A)	$4 m^2$	

similar to “global sensing and global communication” of information by the robots, since in a large group of robots, it is not often practical that a robot communicates with all other robots. On the other hand, Series C uses the half of the range values of Series D. This enables our robots to capture less information, that mimics a close LSLC strategy.

VII. IMPLEMENTATION

Ideally, AFM can be implemented as a complete distributed task-allocation system where each agent selects its own task based on its own external perception about task-urgencies (i.e. attractive fields), distances from tasks and internal task-sensitisation records. Such an implementation requires powerful robots with sophisticated sensors (camera, laser etc.) and sufficient computation and communication capabilities. In that case, robots can keep task-urgency information up-to-date through suitable local communication schemes with their peers who can monitor the tasks. By using suitable navigation and mapping modules, they can also accurately calculate the distances from tasks and navigate to tasks autonomously. Moreover, they also require necessary hardware to do the actual task, e.g. gripper for picking up objects. However, in this study, we are particularly interested to find the suitable communication schemes that can effectively spread the attractive fields (task-urgencies) among robots. So we have simplified the complexities of a full-fledged implementation by using a centralized communication system that effectively makes up the limitations of our e-puck robots. For example, our robots are not capable of sensing a task to estimate its urgencies, instead our centralized TPS broadcast

task information, e.g. task-urgencies, locations etc. to robots in certain time intervals.

In our current implementation, instead of doing any real work with powerful robots, we emulate a mock manufacturing shop-floor scenario that requires the robot only to travel among tasks. As our robots do not have on-board CPU, they need a host PC to control them using BTCom Bluetooth communication protocol over the wireless link [34]. Thus our host-PC runs one RCC for each physical robot. These RCCs also rely upon SwisTrack multi-robot tracking system for updating their real-time pose. So although our MRTA solution is distributed by design, we primarily used a centralized approach to implement it due to the limitations of our robots and the convenience of implementation. Table ?? list the D-Bus communication interfaces among our software components. Fig. ?? outlines the placements of various software components of our multi-robot control architecture based on their functional characteristics and processing requirements [35].

1) *RCC Modules*: As shown in Fig. 4, each e-puck robot is controlled by a corresponding RCC. A RCC sends commands to the robot’s firmware using BTCom protocol. A RCC consists of several Python modules. Each module represents a sub-process under a main process that ties all of them together by using Python’s Multiprocessing module². Below we have described briefly the implementation of these Python modules. All code are publicly accessible through GitHub repository³. In the implementation of RCC, we have employed a data and event management process called DataManager that acts as a data warehouse and event management centre for RCC. Table ?? list the major data structures and corresponding event channels of DataManager. Here mRobotID represents the e-puck robot’s marker ID (converted to decimal number from the binary code) which uniquely identifies a robot from others. We have used Python *dictionary* type data structure for all other data structures that are managed by the Python Multiprocessing’s *Manager()* object. DataManager object also runs

²<http://docs.python.org/library/multiprocessing.html>

³[git://@github.com/roboshepherd/EpuckCentralizedClient.git](https://github.com/roboshepherd/EpuckCentralizedClient.git),
hash:7e3af8902e64db3fa59e

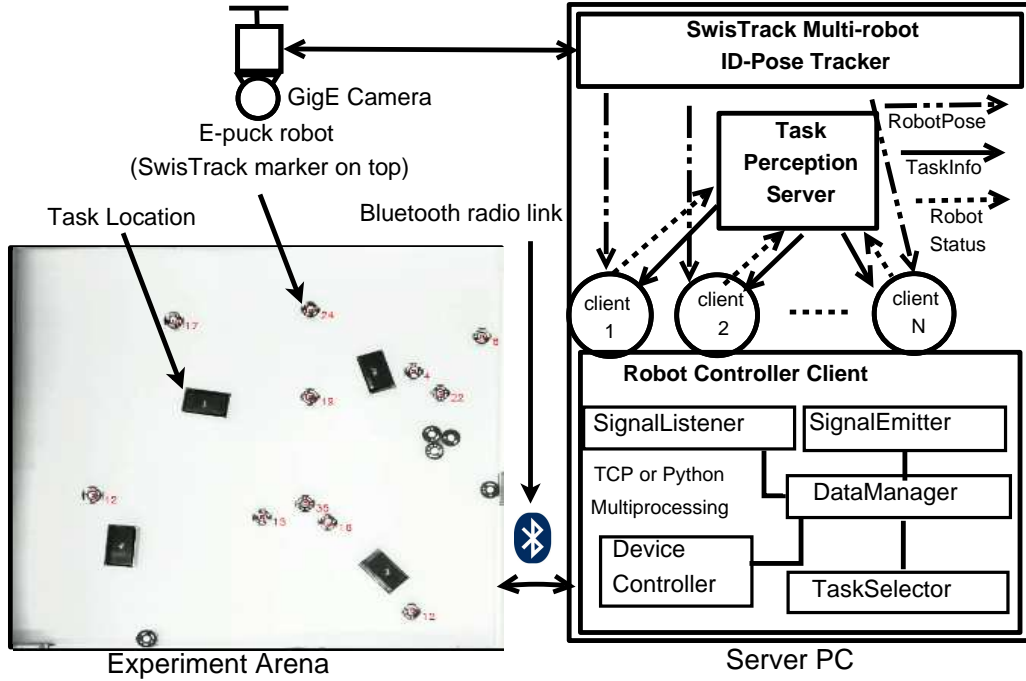


Fig. 4: Hardware and software setup for series A & B experiments

a tiny TCP/IP server process powered by the Multiprocessing's *RemoteManager()* interface. So, if necessary, any other process can access all of the *DataManger*'s data structures and event channels remotely by instantiating a proxy client that connects to this TCP/IP server process.

We have employed two D-Bus communication modules in RCC: *SignalListener* and *SignalEmitter*, that are responsible for listening and emitting D-Bus signals respectively. *SignalListener*, has subscribed to D-Bus session bus for listening to D-Bus *RobotPose* and *TaskInfo* signals. *SignalEmitter* makes use of Python *sched* module that enables it to check periodically *mSelectedTaskStarted* event and emit a robot's task status containing signal, *RobotStatus*. *TaskSelector* works in the application layer of our multi-robot control architecture. It plugs the AFM algorithms (Sec. IV-C) into RCC to select task based-on *DataManger*'s event notifications.

In order to realize LPCM strategy, in the implementation of RCC we have added three new D-Bus signal interfaces. They are briefly specified in Table ?? . Our base implementation of RCC's task-allocation (i.e. *TaskSelector*) is almost unchanged in this local implementation. The only thing we need to extend is the D-Bus signal reception and emission interfaces that catches the above signals and put the signal payload in *DataManger*. For the sake of simplicity, we have merges the perceived *TaskInfo* with communicated *LocalTaskInfo* into one so that *TaskAllocator* always gets all available task information. We have not made any major change in other modules of RCC, i.e. *DeviceController*. The full Python implementation of this RCC is available for download from the GitHub repository⁴.

⁴<http://github.com/roboshepherd/EpuckDistributedClient>

2) *TPS modules*: In our GSNC strategy based implementation of TPS periodically broadcasts TaskInfo signals to all robots using similar D-Bus signal emitting and listening modules. Task information has been updated by a separate Python module following the TPS algorithm described before. In the local version, TPS only emits TaskInfo signal when a robot is within a task's perception range, r_{task} based-on the TaskNeighbour signal from SwisTrack. For this additional interface, we have extended D-Bus SignalListener to catch this additional D-Bus signal. No major changes are done in the other parts of TPS implementation. The full Python implementation of TPS is available for download from the authors' GitHub centralized⁵ and distributed⁶ repositories.

VIII. RESULTS

In this section we have presented our experimental results. We ran those experiments for about 40 minutes duration. They are averaged over five iterations for Series A and B experiments and three iterations for Series C and D experiments.

A. Shop-floor work-load history

In our experiments we have defined shop-floor work-load in terms of task urgencies. For example, Eq. 8 shows how we have calculated initial production work-load of our manufacturing shop-floor scenario. Fig. ?? show the dynamic changes in task-urgencies for the single iteration of each experiment. The fluctuations in these plots are resulted from the different levels of task-performance of our robots. In case of Series D, we can see that an unattended task, *Task4*, was not served by any robot for a long period and later it was picked up by some of the robots. In order to measure the task-related work-loads on our system we have summed up the changes in all task-urgencies over time. We call this as *shop-floor work-load history* and formalized as follows. Let $\phi_{j,q}$ be the urgency of a task j at q^{th} step and $\phi_{j,q+1}$ be the task urgency of $(q+1)^{th}$ step.

⁵<http://github.com/roboshepherd/CentralizedTaskServer>

⁶<http://github.com/roboshepherd/DitributedTaskServer>

We can calculate the sum of changes in urgencies of all M tasks at $(q+1)^{th}$ step:

$$\Delta\Phi_{j,q+1} = \sum_{j=1}^M (\phi_{j,q+1} - \phi_{j,q}) \quad (19)$$

Fig. ?? shows the dynamic shop-floor workload for all four series of experiments. From these plots, we can see that initially the sum of changes of task urgencies (shop-floor workload) is going towards negative direction. This implies that tasks are being served by a high number of robots.

B. Ratio of active workers

From Fig. ??, we can see that in production stage, when work-load is high, many robots are active in tasks. Here active workers ratio is the ratio of those robots that work on tasks to the total number of robots N of a particular experiment. Here we can see that this ratio varies according to the shop-floor work-load changes.

C. Shop-task performance

In our manufacturing shop-floor scenario, we have calculated the APCD and APMW as shown in Fig. ?. For Series A we have got average production completion time 111 time-steps (555s) where sample size is $(5 \times 2) = 10$ tasks, SD = 10 time-steps (50s). According to Eq. 12, our theoretical minimum production completion time is 50 time-steps (250s) assuming the non-stop task performance of all 8 robots with an initial task urgency of 0.5 for 2 tasks and task urgency decrease rate $\Delta\Phi_{DEC} = 0.0025$ per robot per time-step. Hence, Eq. 13 gives us APCD, $\zeta = 1.22$ which means that in Series A experiments, it took 1.22 times more time (305s) than the estimated minimum production completion time (250s). For Series B, we have got average production completion time 165 time-steps (825s) where sample size is $(5 \times 4) = 20$ tasks, SD = 72 time-steps (360s). Hence, Eq. 13 gives us APCD, $\zeta = 2.3$. For Series C we have got average production completion time 121 time-steps (605s) with SD = 36 time-steps (180s). For Series D, average production completion

time is 123 time-steps (615s) with SD = 40 time-steps (200s). According to Eq. 12, our theoretical minimum production completion time is 50 time-steps (250s). The values of APCD are as follows. For Series C, $\zeta = 1.42$ and for Series D, $\zeta = 1.46$. For both series of experiments APCD values are very close.

For APMW, Series A experiments give us an average time length of 369 time-steps (1845s). In this period we have calculated APMW and it is 1 time-step with SD = 1 time-step (5s) and $\Delta\Phi_{INC} = 0.005$ per task per time-step. This shows a very low APMW ($\chi = 0.000235$) implying a very high robustness of our system. For Series B experiments, from the average 315 time-steps (1575s) maintenance activity of our robots per experiment run, we have got APMW, $\chi = 0.012756$ which corresponds to the pending work of 3 time-steps (15s) where SD = 13 time-steps (65s). This also tells us the robust task performance of our robots which can return to an abandoned task within a minute or so. The APMW of Series C experiments give us an average time length of 359 time-steps (1795s). In this period we calculated APMW and it is 5 time-steps with SD = 17 time-steps and $\chi = 0.023420$. For Series D experiments, from the average 357 time-steps (1575s) of maintenance activity of our robots per experiment run, we have got APMW, $\chi = 0.005359$ which corresponds to the pending work of 2 time-steps (10s) where SD = 7 time-steps.

D. Task specializations

We have measured the task-specialization of the robots based-on their peak value of sensitization. This maximum value represents how long a robot has repeatedly been selecting a particular task. Since tasks are homogeneous we have considered the maximum sensitization value of a robot among all tasks during an experiment run. This value is then averaged for all robots using the following equation.

$$K_{avg}^G = \frac{1}{N} \sum_{i=1}^N \max_{j=1}^M (k_{j,q}^i) \quad (20)$$

If a robot r_i has the peak sensitization value k_j^i on task j ($j \in M$) at q^{th} time-step, Eq. 20 calculates

the average of the peak task-specialization values of all robots for a certain iteration of our experiments. We have also averaged the time-step values (q) taken to reach those peak values for all robots using the following equation.

$$Q_{avg}^G = \frac{1}{N} \sum_{i=1}^N q_{k=k_{max}}^i \quad (21)$$

In Eq. 21, $q_{k=k_{max}}^i$ represents the time-step of robot r_i where its sensitization value k reaches the peak k_{max} as discussed above. By averaging this peak time-step values of all robots we can have an overall idea of how many task-execution cycles are spent to reach the maximum task-specialization value K_{avg}^G . Table ?? and Table ?? show the peak sensitization values of Series A and Series B experiments respectively. Based on Eq. 20 and Eq. 21, we have got the peak task-sensitization K_{avg}^G values: 0.40 (SD=0.08) and 0.30 (SD=0.03), and their respective time-step Q_{avg}^G values: 38 (SD=13) and 18 (SD=5) time-step. They are shown in Fig. ???. Here we can see that the robots in Series A had higher chances of task-specialization than that of Series B experiments.

E. Robot motions

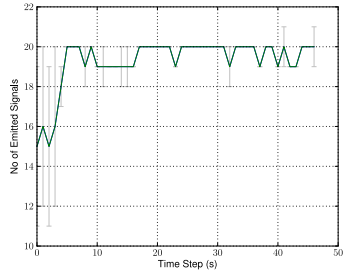
We have aggregated the changes in translation motion of all robots over time based on their travelled distances in Euclidean metric. Let $u_{i,q}$ and $u_{i,q+1}$ be the translations of a robot i in two consecutive steps. If the difference between these two translations be δu_i , we can find the sum of changes of translations of all robots in $(q+1)^{th}$ step using the following equation.

$$\Delta U_{q+1} = \sum_{i=1}^N \delta u_{i,q+1} \quad (22)$$

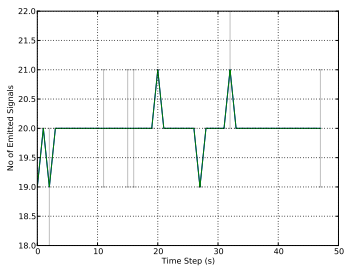
The sum of translations of robots from our experiments are plotted in Fig. ???. In this plot we can see that robot translations also vary over varying task requirements of tasks.

F. Communication load

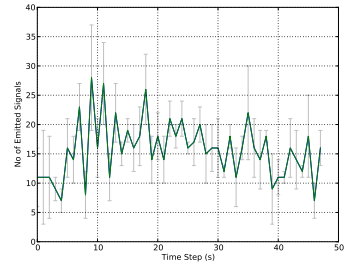
Fig. 13 (a) and (b) shows the number of received TaskInfo signals by each robot in Series A and



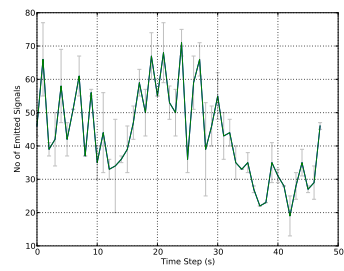
(a) Series A



(b) Series B



(c) Series C



(d) Series D

Fig. 13: Frequency of TaskInfo signalling of (a) and (b) by TPS and (c) and (d) by local peers.

Series B experiments. Since the duration of each time-step is 50s long and TPS emits signal in every 2.5s, there is an average of 20 signals in each time-step. The overall P2P task information signals of both of these local modes are plotted in Fig. 13 (c) and (d). As an example of P2P signal reception of a robot, Fig. ?? show the number of received signals by *Robot12* in two local experiments. It states the relative difference of peers over time in two different cases.

IX. DISCUSSIONS

A. Self-regulated MRTA

From our experimental results, we have noted several aspects of self-regulated MRTA that expose the effectiveness of AFM. As we have pointed out that this self-regulated MRTA, as observed in biological and human social systems, needs to satisfy several important characteristics, particularly plasticity and task-specialization. In addition to satisfying those basic qualities, AFM has demonstrated many other aspects. Our self-regulated robots, driven by AFM, effectively handle the dynamic work-load in our manufacturing shop-floor. They can dynamically support the need to work on demanding tasks, if there any. The variations of active worker ratio shows this.

From the self-organized worker allocations of AFM, it is clear to us that although in larger system (Series B) the degree of variations of active-worker ratio can show us significantly unpredictable patterns, nevertheless the self-regulated rules drive the robots to respond to the dynamic needs of the system. This means that AFM can sufficiently produce the plasticity of DOL in order to meet the dynamic work-load of the system.

B. Learning and forgetting

From the individual and group-level task-specialization, we can see that robots can maintain both task-specialization and flexibility. In a self-organized system, it is very common that only a few individuals specialize on tasks and others generally do not. From two sample data sets provided in

Table ?? and Table ??, we can see that in particular runs of Series A and Series B experiments, task-sensitization values of only 2-3 robots reach above the group-level average score. Thus in both types of experiments, robots exhibit similar task-specialization behaviours.

C. Concurrency and robustness

As a consequence of fewer robots specializing in tasks, we can also see that robots can concurrently consider different tasks without being biased to a particular task all the time. Our experiments also show us the robust MRTA as in case of both high and low work-loads present in the system. This is evident from the manufacturing shop-floor task performance during PMM and MOM. For example, in case of Series B experiments APMW was 13 time-steps (65s) which corresponded to pending work-load of 0.065 unit for a single robot. Thus, on an average, before the work-load exceeded by about 13 percent of initial work-load, robots were able to respond to a task.

D. Communication load

In GSNC strategy based experiments we used a centralized communication system (source of attractive fields) that serves the robots with necessary task-perception information. Our centralized communication system has the advantage of minimising the communication load and the disadvantage of a single point of failure as well as a single point of load. Under LSLC strategy based implementation, we present how the task perception can be decentralized by P2P communications among RCCs.

E. Scaling-up

We have observed the effect of scaling-up the robot team size. The system size of Series B is double of that of Series A in terms of robots, tasks and experiment arena. Keeping a fixed ratio of robot-to-task and task-to-arena we have intended to see the scaling effects in our experiments. Here we see that both systems can show sufficient self-regulated DOL, but task-performance of both systems varies significantly. For example, the value of APCD

in Series B is higher by 1.08. This means that performance is decreased in Series B experiments despite having the resources in same proportion in both systems. This occurs partly due to the greater stochastic effects found in task-allocation in a larger system, e.g. presence of more tasks produce higher stochastic behaviours in robot's task selection.

Similarly we can see that in larger system robots have less chances to specialize on tasks, as the Series B experiments show us that the overall average task-specialization of the group K_{avg}^G is lower by 0.10 and it lasts for significantly less time (the difference of Q_{avg}^G of both systems is 20 time-steps). Thus, in a large group, robots are more likely to switch among tasks more frequently and this produces more translation motions which cost more energy (e.g. battery power) in task-performance.

F. Comparisons between GSNC and LSLC strategies

Results from Series C and Series D experiments show many similarities and differences with respect to the results of Series A and Series B experiments. As shown in Table ?? both Series C and Series D experiments show similar production delay (APCD) values: 605s and 615s respectively, which are less than Series B experiment result (825s) and are close to Series A experiment result (555s). Note that all statistical t-test results are obtained with respect to Series C data and it shows that there is no significant difference in task-performance between Series B and Series C results. Besides, in terms of task-specialization as shown in Table ??, the overall task-specialization of group in Series C ($K_{avg}^G = 0.4$) is closer to that of Series A experiments ($K_{avg}^G = 0.39$) and interestingly, the value of Series D ($K_{avg}^G = 0.27$) is much closer to that of Series B experiments ($K_{avg}^G = 0.30$). So task-specialization in large group under LSLC strategy is not significantly different than their GSNC counter part.

Table ?? summarizes the average translations done by robots in all four series of experiments. From these robot motion profiles, it is found that under LSLC strategy, robot translations have been reduced significantly. From this table it is seen than Series C and Series D show about 2.8 times less

translation than that in Series B experiments. The translation of 16 robots in Series C and Series D experiments are approximately double (1.89 times) than that of Series A experiments with 8 robots. Thus the energy-efficiency under LSLC strategy seems to be higher than that under GSNC strategy.

From the above results one can see that large group robots achieve similar or better MRTA under LSLC strategy. The local sensing of tasks prevents them to attend a far-reaching task which may be more common under global sensing strategy. However, as it is seen in Fig. ?? some tasks can be left unattended for a long period of time due to the failure to discover it by any robot. For that reason it is seen that the values of pending maintenance load is slightly higher under LSLC strategy. But this trade-off is worth as LSLC strategy provides superior self-regulated MRTA in terms of task-performance, task-specialization and energy-efficiency.

X. CONCLUSION AND FUTURE WORKS

The benefits of deploying a large number of robots in dynamic multi-tasking environment can not be fully realized without adopting an effective communication and sensing strategy for a given multi-robot system. This study has focused on comparing two bio-inspired communication and sensing strategies in producing self-regulated MRTA by an interdisciplinary model of DOL, AFM. Under the GSNC strategy, AFM has produced the desired self-regulated MRTA among a group of 8 and 16 robots. This gives us the evidence that AFM can successfully solve the MRTA issue of a complex multi-tasking environment like a manufacturing shop-floor. Under the LSLC strategy, AFM can also produce the desired self-regulated MRTA for 16 robots with different communication and sensing ranges.

From our comparative results, we note that for large group of robots, degradation in task-performance and task-specialization of robots are likely to occur under GSNC strategy that relies upon a centralized communication system. Thus GSNC strategy can give us better performance when the number of tasks and robots are relatively small. This confirms us the assertions made by some biologists

that self-regulated DOL among small group of individuals can happen without any significant amount of local communications and interactions. However, our findings suggest that task-specialization can still be beneficial among the individuals of a small group which contradicts the claim that small groups only possess the generalist workers, but not the specialists.

On the other hand, LSLC strategy is more suitable for large group of individuals that are likely to be unable to perform global sensing and global communications with all individuals of the group. The design of communication and sensing range has still remained as a critical research issue. However, our results suggest that the idea of maximizing information gain is not appropriate under a stochastic task-allocation process. Here more information tends to cause more task-switching behaviours that lowers the level of task-specialization of the group. This might not be the case under a deterministic task-allocation scheme where more information may lead to better and optimum allocations in a small group of individuals. Nevertheless, despite having the limited communication and sensing range, LSLC strategy has helped the robots to produce comparatively better task-allocation with increased task-specialization and significantly reduced motions or savings in energy consumption.

REFERENCES

- [1] R. C. Arkin, *Behavior-based robotics*. Cambridge, Mass.: MIT Press, c1998., 1998, includes bibliographical references (p. [445]-476) and indexes.
- [2] L. E. Parker and F. Tang, "Building multirobot coalitions through automated task solution synthesis," *Proceedings of the IEEE*, vol. 94, pp. 1289–1305, 2006.
- [3] B. P. Gerkey and M. J. Mataric, "A formal analysis and taxonomy of task allocation in multi-robot systems," *The International Journal of Robotics Research*, vol. 23, p. 939, 2004.
- [4] A. B. Sendova-Franks and N. R. Franks, "Self-assembly, self-organization and division of labour," *Philosophical Transactions of the Royal Society of London B*, vol. 354, pp. 1395–1405, 1999.
- [5] B. Gerkey and M. Mataric, "Multi-robot task allocation: analyzing the complexity and optimality of key architectures," *Robotics and Automation, 2003. Proceedings. ICRA'03. IEEE International Conference on*, vol. 3, 2003.
- [6] L. E. Parker, "Distributed intelligence: Overview of the field and its application in multi-robot systems," *Journal of Physical Agents, special issue on multi-robot systems*, vol. 2, no. 2, pp. 5–14, 2008.
- [7] L. Chaimowicz, M. F. M. Campos, and V. Kumar, "Dynamic role assignment for cooperative robots," *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on*, vol. 1, 2002.
- [8] M. B. Dias, R. M. Zlot, N. Kalra, and A. Stentz, "Market-based multirobot coordination: A survey and analysis," *Proceedings of the IEEE*, vol. 94, pp. 1257–1270, 2006.
- [9] K. Lerman, C. Jones, A. Galstyan, and M. J. Mataric, "Analysis of dynamic task allocation in multi-robot systems," *The International Journal of Robotics Research*, vol. 25, p. 225, 2006.
- [10] C. R. Kube and H. Zhang, "Collective robotics: From social insects to robots," *Adaptive Behavior*, vol. 2, p. 189, 1993.
- [11] W. Liu, A. F. T. Winfield, J. Sa, J. Chen, and L. Dou, "Towards energy optimization: Emergent task allocation in a swarm of foraging robots," *Adaptive Behavior*, vol. 15, no. 3, pp. 289–305, 2007.
- [12] E. Arcaute, K. Christensen, A. Sendova-Franks, T. Dahl, A. Espinosa, and H. J. Jensen, "Division of labour in ant colonies in terms of attractive fields," *Ecol. Complexity*, 2008.
- [13] R. Jeanne, "Group size, productivity, and information flow in social wasps," *Information processing in social insects*, pp. 3–30, 1999.
- [14] L. E. Parker, "Alliance: an architecture for fault tolerant multirobot cooperation," *Robotics and Automation, IEEE Transactions on*, vol. 14, pp. 220–240, 1998.
- [15] W. Shen, D. H. Norrie, and J.-P. Barthes, *Multi-agent systems for concurrent intelligent design and manufacturing*. London: Taylor & Francis, 2001.
- [16] P. Stone and M. Veloso, "Task decomposition, dynamic role assignment, and low-bandwidth communication for real-time strategic teamwork," *Artificial Intelligence*, vol. 110, pp. 241–273, 1999.
- [17] C. Belta and V. Kumar, "Abstraction and control for groups of robots," *IEEE Transactions on Robotics*, vol. 20, no. 5, pp. 865–875, 2004.
- [18] G. Pereira, V. Kumar, and M. Campos, "Decentralized algorithms for multirobot manipulation via caging," *Algorithmic Foundations of Robotics V*, pp. 257–274, 2003.
- [19] T. Dahl, M. Mataric, and G. Sukhatme, "Distributed multi-robot task allocation through vacancy chains," *Autonomous Robots*, 2004.
- [20] S. Camazine, N. Franks, J. Sneyd, E. Bonabeau, J. Deneubourg, and G. Theraula, *Self-organization in biological systems*. Princeton, N.J.: Princeton University Press, c2001., 2001, what is self-organization? – How self-organization works – Characteristics of self-organizing systems – Alternatives to self-organization –.
- [21] E. Bonabeau, M. Dorigo, and G. Theraulaz, *Swarm intelligence: from natural to artificial systems*. Oxford University Press, 1999.
- [22] M. Krieger and J. Billeter, "The call of duty: Self-organised task allocation in a population of up to twelve mobile robots," *Robotics and Autonomous Systems*, vol. 30, no. 1-2, pp. 65–84, 2000.

- [23] W. Agassounon and A. Martinoli, "Efficiency and robustness of threshold-based distributed allocation algorithms in multi-agent systems," in *Proceedings of the first international joint conference on Autonomous agents and multiagent systems: part 3*. ACM, 2002, p. 1097.
- [24] C. Jones and M. Mataric, "Adaptive division of labor in large-scale minimalist multi-robot systems," in *2003 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2003.(IROS 2003). Proceedings*, 2003.
- [25] N. Kalra and A. Martinoli, "A comparative study of market-based and threshold-based task allocation," *Distributed Autonomous Robotic Systems* 7, pp. 91–101, 2007.
- [26] B. B. Werger and M. J. Mataric, "Broadcast of local eligibility for multi-target observation," *Distributed Autonomous Robotic Systems*, vol. 4, p. 347356, 2001.
- [27] S. Botelho, R. Alami, and T. LAAS-CNRS, "M+: a scheme for multi-robot cooperation through negotiated taskallocation and achievement," *Proceedings IEEE International Conference on Robotics and Automation*, vol. 2, 1999.
- [28] B. P. Gerkey and M. J. Mataric, "Sold!: Auction methods for multirobot coordination," *IEEE Transaction on Robotics and Automation*, vol. 18, 2002.
- [29] R. Zlot, A. Stentz, M. Dias, and S. Thayer, "Multi-robot exploration controlled by a market economy," *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on*, vol. 3, 2002.
- [30] H. Çelikkanat, A. Turgut, and E. Şahin, "Guiding a robot flock via informed robots," *Distributed Autonomous Robotic Systems* 8, pp. 215–225, 2008.
- [31] B. Gerkey and M. Mataric, "Principled communication for dynamic multi-robot task allocation," *Experimental Robotics VII*, pp. 353–362, 2001.
- [32] B. Holldobler and E. Wilson, *The ants*. Belknap Press, 1990.
- [33] E. Yoshida and T. Arai, "Performance analysis of local communication by cooperating mobile robots," *IEICE Transactions on Communications*, vol. 83, no. 5, pp. 1048–1059, 2000.
- [34] F. Mondada, M. Bonani, X. Raemy, J. Pugh, C. Cianci, A. Kłaptocz, S. Magnenat, J. Zufferey, D. Floreano, and A. Martinoli, "The e-puck, a robot designed for education in engineering," in *Proc. of the 9th Conf. on Autonomous Robot Systems and Competitions*, 2009.
- [35] M. Sarker and T. Dahl, "Flexible Communication in Multi-robotic Control System Using HEAD: Hybrid Event-driven Architecture on D-Bus," in *In Proc. of the UKACC International Conference on Control 2010 (CONTROL 2010)*, to appear, 2010.