Making Collective Behaviours to work through Implicit Communication

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***Abstract*— The aim of this paper is to investigate how stigmergic information allow each individual of a group of autonomous robots to take advantages from other individual behaviors. The proposed analysis is based on the roboticle model where sensor data and effector commands are treated as energy exchange between the robot and its environment, eventually populated by other robots. Without explicit communication, the collective behavior of a group of teammates can be forced only if the robot designer makes each robot to become aware of distinguishing configuration patterns in the environment. Usually, the job is accomplished both by evaluating descriptive conditions as macroparameters and an appropriate dynamic role assignment among teammates. Since observed individual behaviors can affect the normal course of operations for each robot propagating to other teammates, we want to address some issues on how a collective behavior is fired and maintained.**

***Index Terms*— Stigmergy, Multirobot, Cooperation, Roboticle**

I. Introduction

The challenge that a colony of robots [6] [18] can successfully perform a collective task becomes a much more ambitious goal when flexibility, reliability and safety in human-machine interaction are also required. The emergence of cooperative abilities depends on the many communication schemas to be used in different scenarios where robots are situated and cooperate. Thus, cooperation always requires communication which doesn't imply negotiation.

A commonly accepted approach to this issue stems from the observation that not only robots but even exchanged information must be situated in the environment. Natural agents, such as many animals and humans, make use of this capability referred as *stigmergy* in biological literature. More generally, *stigmergy* can be interpreted as a social circumstance by which agents interact by affecting their environment rather than explicitly communicating each other [11]. Also the notion of *affordance* can be used in this context.

The term *stigmergy* was first used by the French biologist Pierre-Paul Grasse[14], studying how ant and termite colonies work. These groups of social insects can perform complex collective tasks, such as building shelter, finding and retrieving food, without any symbolic communication which cannot be provided by their absolutely tiny brains. Grasse found that individual insects use pheremones to change their environment, and that other insects follow these pheremones reflexively.

Thus, *mobility* and *stigmergy* play a crucial role in forcing a collective behavior of a group of autonomous agents to achieve common goals. Also Mataric[16] considers implicit cooperation and indirect communication basic properties for collective task execution. A completely different approach is due to the distributed artificial intelligence community who has made many attempts to understand collective behaviors in terms of symbolic manipulation [21], [15], [10].

But, after the introduction of the so called behaviour-based architectures [4], [1], [2], it seems more natural to think of intelligence as an emergent property [17], [22], [5] rather than a set of very specialized functions to be implemented as complex symbol-manipulating algorithms. More recently Asama [12] has coined the term *mobiligence* referred to intelligence which emerges through the interaction between an agent and its environment due to its mobility.

In its seminal paper Asama suggests three properties to be supplied in order to make emerging intelligence, namely, *embodied plasticity*, *abduction* and *co-embodiment* with the environment. The second one would cope with the ability of an autonomous agent to import environmental information inside it with the aim to become more adaptive within the environment over the time.

With the same respect, the roboticle model [7] argues that agent *mobility* and *autopoiesis* could provide a proper framework where to cast operating intelligence. In fact, autopoiesis deals with the basic feature of an agent: *acquire information from the environment as perceptual energy to be metabolized and, then, delivered outside as effector commands when it were appropriate*.

II. Autopoiesis

The roboticle model assumes three different properties: situatedness, embodiment and mobility from which evolves

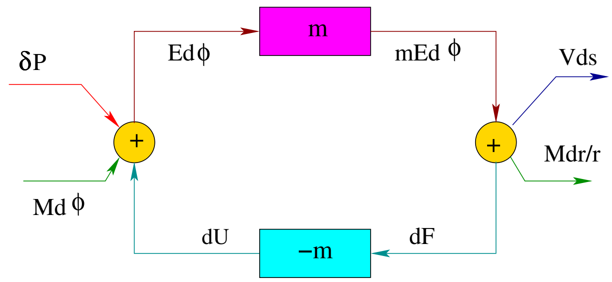

Fig. 1. Autopoietic loop

the so called *autopoietic loop*. It appears as the fundamental mechanism by which agents can acquire information about the environment and it is particularly suitable when such information deals with the trajectory covering of individuals of a robot colony. In this case, stigmergic information enters the governor's control unit as *perceptual perturbation* to be manipulated for the objectives of the common goal to be pursued.

Robot effectors are driven by dissipating a congruous amount of *effort*, previously accumulated within the autopoietic loop, which changes the quality of the entering energy from disordered into more ordered one. So, an adaptive robot exhibits the specific ability of triggering the perceptual energy flow towards its effectors, where dissipation is made in according to the best expected results.

Thus, autopoiesis behaves as a tool to deal qualitatively with cooperation between individuals inside a group. First of all, the designer must depict the autopoietic loop for each individual, especially emphasizing those features which are addressed by the required collective behavior. The fig. 1 illustrates the autopoietic loop which refers to one of the two identical interacting roboticles in the example discussed in the next sections.

Secondly, he should specify what individuals are requested to cooperate on the basis of what exchanged information. At this point, the designer can draw an oriented arc connecting two autopoietic loops. The former refers to the robot whose released actions suggest the latter to exhibit a well specified behavior. The arc is eventually labelled by the *exchanged energy* which exits the former loop as a delivered effort and enters the latter as perceptual perturbation.

In the rest of the paper we shall discuss with some detail how two or more autopoietic loops are really involved in this kind of energy exchange and how it can perturbate the trajectory covering of an autonomous vehicle by affecting its mobility. Moreover, mobility itself is considered a source of stigmergic information.

III. Roboticle Interaction

The roboticle model [9] assumes a wheel-driven autonomous robot to be reduced to a well-specified point having the property that its *speed* and its *direction* are the *speed* and the *steering* of the mobile platform. In this sense it generalizes the concept of *particle* used in mechanics and it refers to the ability of an autonomous robot to explore its environment both to learn about it and to accomplish its task.

The characterization of the roboticle model stems from the so called *mobility assumption* requiring the trajectory covering in the environment to take the form

$$\begin{aligned} \dot{x} &= u(x,y) \\ \dot{y} &= v(x,y) \end{aligned} \qquad (1)$$

In this context, we can derive the preceding dynamical law by the means of a dissipative component due to the **dissipative function** F, and a conservative component due to the **internal energy** U

$$\begin{aligned} u &= -\frac{\partial F}{\partial x} - \frac{\partial U}{\partial y} \\ v &= -\frac{\partial F}{\partial y} + \frac{\partial U}{\partial x} \end{aligned} \qquad (2)$$

It triggers the actual trajectory covering by assimilating the amount of **perceptual perturbation** δP the agent's governor unit converts into delivered **effort** *Vds*, accordingly to the following relations

$$\begin{aligned} \delta P &= vdx - udy \\ Vds &= udx + vdy \end{aligned} \qquad (3)$$

with the property to resist to external disturbances and to maintain its internal order of operations.

A. Mutual Committing

Now, let us consider a robot which partecipates to a collective task where two or more actions are released simultaneously by different individuals within the same shared environment. As previously stated, the use of stigmergic communication is very common in the biological world, so we have tried to exploit this feature in our roboticle model.

We shall begin our discussion from a short analysis of how the autopoietic loop triggers the delivered effort *Vds* while it's responding to the perceptual stimulus δP. First of all, the presence of both conservative and dissipative components, plays a fundamental role, especially the dissipative component. In fact, substituting *u* and *v* appearing in (3) for the expression given by (2), we can write

$$\begin{aligned} \delta P - \delta L &= dU \\ \delta Q - Vds &= dF \end{aligned} \qquad (4)$$

where the new two quantities δL and δQ, called **committing effort** and **committed perception** respectively, are

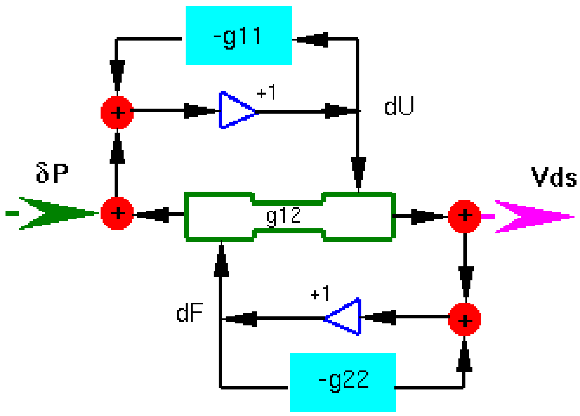

Fig. 2. General autopoietic loop

defined by the differential relations appearing below

$$\begin{aligned} \delta L &= \tfrac{\partial F}{\partial x}dy - \tfrac{\partial F}{\partial y}dx \\ \delta Q &= \tfrac{\partial U}{\partial x}dy - \tfrac{\partial U}{\partial y}dx \end{aligned} \quad (5)$$

Even if their evaluation is central to understand how the autopoietic loop works with the respect to a specified dynamical law, their meaning is much more general and it depends on how the perceptual apparatus sends relevant information to trigger robot effectors.

From this point of view, in the spirit of the discussion appearing in [9], we can write more general relations such as

$$\begin{aligned} \delta L &= g_{11}dU - g_{12}dF \\ \delta Q &= g_{21}dU - g_{22}dF \end{aligned} \quad (6)$$

from which we can depict the autopoietic loop shown in fig. 2 and whose terms g_{ij} depend on the specific implementation of robot governor's unit.

B. Connective Function

As it has been pointed out in our preceding works [7], [8], the dissipative function F plays a crucial role for the stabilization of the autopoietic loop. With the same perspective we shall assume that, when two or more roboticles are put together inside an arena, the completion of a collective behavior should be triggered by reshaping the dissipative function of the group with a set of terms expressing the requested interactions between designated individuals.

Thus, let us assume an arena to be populated by a group of N roboticles $\{R_1, R_2, ..., R_N\}$, each of which characterized by the tupla $\{F_i, U_i\}$. If we want such a group to become a roboticle team, we need each individual to exhibit the aptitude to perform some cooperative task. In the roboticle model this requirement is featured by an appropriate dissipative function of the team. Its formulation is made by summing up the dissipative function of each individual component and subtracting as many terms M_{ij} as necessary to represent the interaction among all the designated individuals.

Under the preceding hypothesis, we can write the following relations for the roboticle team

$$\begin{aligned} F &= \sum_{i=1}^{N} F_i - \sum_{i,j=1}^{N} M_{ij} \\ U &= \sum_{i=1}^{N} U_i \end{aligned}$$

involving both the dissipative function and the internal energy of each individual roboticle. The additional terms M_{ij}, appearing in the expression of the dissipative function are named **connective functions** and they provide all the necessary *perceptual perturbations* to implement the distributed sensing and acting capabilities of the team while it carries out the collective task.

The meaning of each term M_{ij} is that of perturbing the trajectory covering of a single roboticle R_i by a dissipative component for each interacting roboticle R_j. Using a polar frame of reference such a perturbation takes the form

$$\begin{aligned} \dot{r}_i &= \xi_i(r_i, \varphi_i) + \tfrac{\partial M_{ij}}{\partial r_i} \\ r_i\dot{\varphi}_i &= \eta_i(r_i, \varphi_i) + \tfrac{1}{r_i}\tfrac{\partial M_{ij}}{\partial \varphi_i} \end{aligned}$$

where the differential terms, appearing in the right side of each equation, implement the cooperation between the roboticles R_i and R_j. With the same respect we are able to specify how the unperturbed trajectory of a single roboticle is modified by the interaction with other individuals, making explicit the result of how the exchanged stigmergic energy succeds in altering the course of actions for individual roboticles.

IV. Twin Followers

For the sake of clarity, let us consider the case of two identical vehicles which are moving around a fixed light source. The example is in the spirit of Braitenberg's vehicles [3] within a simple but meaningful environment where vehicles are embedded with appropriate motor and sensor devices. Before entering the core of the discussion we need another important result within the roboticle model. As it has been suggested in [7], [8], the same dynamical law (1) can be derived from the following equations

$$\begin{aligned} u &= -E(x,y)\tfrac{\partial S}{\partial y} \\ v &= +E(x,y)\tfrac{\partial S}{\partial x} \end{aligned} \quad (7)$$

where *E(x,y)* is the so called **total energy** whereas the quantity *S(x,y)* is the implicit representation of the **nominal trajectory** to be covered by the roboticle. The actual trajectory could significantly differ from the nominal so, usually, the designer is not requested to have care for its accurate definition. On the contrary, much more attention should be devoted to the *control mechanism* embedded in what we have called the autopietic loop of the robot.

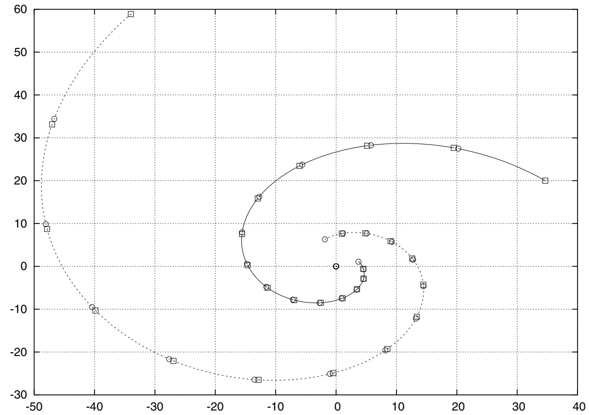

Fig. 3. Uncoupled vehicles

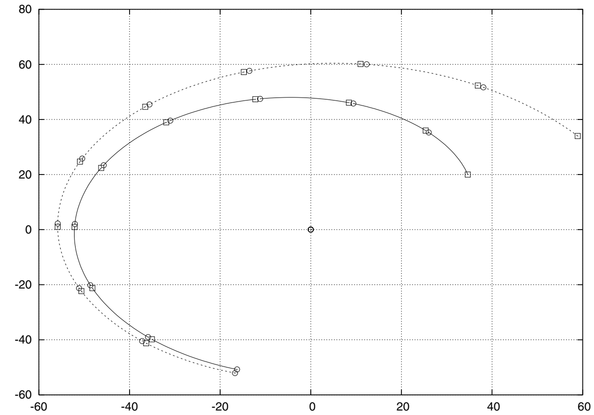

Fig. 4. Twin followers with k=1

A. Unlinked Vehicle

First of all, we implement each vehicle indipendently and we choose to force the corresponding roboticle to behave as a vehicle which approaches some fixed light source smoothly with a given constant rate. Thus, the speed and steering control laws take the simple form

$$\begin{aligned} \dot{V} &= -\tfrac{V}{\tau} \\ \dot{\theta} &= \omega_0 \end{aligned} \quad (8)$$

which is an open-loop control because there is no sensor detection of the course of actions. It should be noticed, however, that such relations stem from a roboticle model which assumes the following internal energy and dissipative function

$$\begin{aligned} U(r) &= \tfrac{\omega_0 r^2}{2} \\ F(r) &= \tfrac{r^2}{2\tau} \end{aligned}$$

accordingly to [9] with ω_0 and τ the same constant values appearing in (8).

Within this simple scenario we have assumed a polar frame of reference centered on the fixed light source. In this case the total energy and the implicit nominal trajectory are easily determined

$$\begin{aligned} E(r) &= \tfrac{r^2}{\tau} \\ S(r,\varphi) &= m \log \tfrac{r}{a} + \varphi \end{aligned} \quad (9)$$

with a an arbitrary constant and m given by the product $\omega_0 \tau$. The corresponding dynamical law is

$$\begin{aligned} \dot{r} &= -\tfrac{r}{\tau} \\ \dot{\varphi} &= \omega_0 \end{aligned} \quad (10)$$

which allows us to get a better control law to drive each vehicle. In fact, from the easy to prove identities $\dot{r} = V\cos(\theta-\varphi)$ and $r\dot{\varphi} = V\sin(\theta-\varphi)$, the application of the total time derivative operator to both equations yields

$$\begin{aligned} \dot{V} &= -\tfrac{V}{\tau} + q(\theta-\varphi)V\sin(\theta-\varphi) \\ \dot{\theta} &= \omega_0 + q(\theta-\varphi)\cos(\theta-\varphi) \end{aligned} \quad (11)$$

taking into account (10), with $q(\beta)$ a well specified virtual sensor providing the following information

$$q(\beta) = \frac{1}{\tau}(\sin(\beta) + m\cos(\beta))$$

Comparing the preceding relations (11) with (8), it appears that the additional terms containing $q(\beta)$ close the roboticle-environment loop as it is required by any behavior-based approach. To understand the meaning of such a term you must take the total time derivative of $S(r,\varphi)$ appearing in (9) and yielding, after simple manipulations and some substitutions,

$$\dot{S} = \frac{\sqrt{1+m^2}}{\tau}\left(m\cos(\theta-\varphi) + \sin(\theta-\varphi)\right)$$

so that $q(\theta-\varphi)$ provides an output which differs from the amount of change of S over the time only by a constant factor.

B. Linked Vehicles

Now, let us suppose two such vehicles moving around on the same plane surface with the light source which triggers their motion according to (11). The trajectories of both vehicles don't depend on each other as shown in fig. 3.

A completely different situation appears if we assume the two vehicles are exchanging stigmergic information, namely, *cooperation without explicit communication*. As previously noticed, we can force such a condition by providing the dissipative function of the two interacting vehicles with a new term *M* which depends on positional coordinates of both vehicles. In our example we assume

$$M(r_1, r_2) = k\frac{r_1 r_2}{\tau}$$

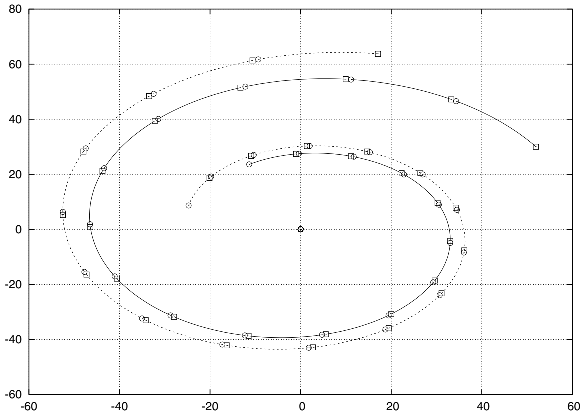

Fig. 5. Twin followers with k=0.7

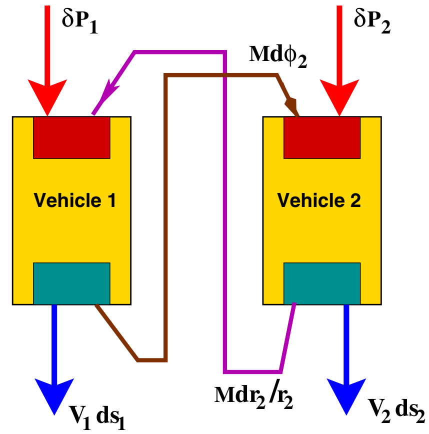

Fig. 6. Twin vehicles autopoietic loop

where k is a positive constant value ranging over $[0..1]$. Now, the dynamical law becomes

$$\begin{array}{rclrcl} \dot{r_1} & = & -\frac{1}{\tau}(r_1 - kr_2) & \dot{r_2} & = & -\frac{1}{\tau}(r_2 - kr_1) \\ \dot{\varphi_1} & = & \omega_0 & \dot{\varphi_2} & = & \omega_0 \end{array}$$

and the trajectory covering of each individual vehicle depends on the amount of interaction between them. In fig. 4 it has been shown two running vehicles having $k = 1$. A different interaction pattern appears when we take the value $k = 0.7$ as depicted in fig. 5.

The emergent behavior exhibited by the twin vehicles discussed in this example can be better understood if we interpret the constant value k as the cosine of a given angle α. In this case the dissipative function can be compacted into the following relation

$$F = \frac{1}{2\tau}|\mathbf{r}_1 - \mathbf{r}_2|^2$$

with $\mathbf{r}_1$ and $\mathbf{r}_2$ the radius vectors of the corresponding two roboticles. So, because α is the fixed phase difference of such vectors, we can observe a collective behavior of two running vehicles which approach the light source with the slower following the faster while their speeds are converging to maintain a fixed distance over the time.

However, the actual control of each vehicle must be implemented as speed and steering regulation in the spirit of the analougous relations (11). So, if we apply the total time derivative operator to both equations expressing the dynamical law for the former vehicle, we obtain

$$\begin{array}{rcl} \dot{V}_1 & = & -\frac{V_1}{\tau} + [q(\theta_1 - \varphi_1) + \\ & & p(r_2/r_1)\cos(\theta_1 - \varphi_1)V_1]\sin(\theta_1 - \varphi_1) \\ \dot{\theta}_1 & = & \omega_0 - p(r_2/r_1) + [q(\theta_1 - \varphi_1) + \\ & & p(r_2/r_1)\cos(\theta_1 - \varphi_1)]\cos(\theta_1 - \varphi_1) \end{array} \quad (12)$$

where $p(z)$ is a new virtual sensor which provides the information

$$p(z) = \frac{1}{\tau}\frac{k}{m}(k - z)$$

effective for the vehicle to align its trajectory to the latter. The pecularity of this sensor is found in the specific parameter **z**, used to extract the required information. In this simple case, referred to the abstract example of two running vehicles, it is *the ratio* r_2/r_1 *between the distances of the two vehicles from the light source* to play the role to make emerging the just described collective behavior. In our preceding works [13], [19], [20] we have called this quantity **macroparameter** with the aim to assign to a specified perceptive pattern a scalar value to be useful to make a decision about what behavior to activate next.

C. Autopoietic Loop

In the preceding discussion we have shown how macroparameters can change the normal course of actions for a single robot to make it partecipating to a collective action. This result stems from the stigmergic information acquired through sensors and which triggers effectors. But, in sect. 2 we have argued that the mechanism by which an autonomous vehicle is governed is just the so called *autopoietic loop*.

In the previously discussed example, it is the supplementary term M which plays the role of storing the stigmergic information which enter each individual autopoietic loop as *perceptual perturbation*. In fact, from (3) and following the same method discussed in [7], we get

$$\delta P_1 = E_1 dS_1 - M d\varphi_1$$

where E_1 and S_1 have the same form of (9) with the explicit subscript referred to the former vehicle. Thus, combining them, it is easy to obtain the following relation

$$\delta P_1 + M d\varphi_1 = dU_1 + mE_1 d\varphi_1$$

where the left side includes two different perceptual terms. The former accomodates the necessary adapting information to adjust the trajectory component due to the vehicle itself. The latter defines the stigmergic energy entering the governor's control unit due to its companion vehicle.

An analogous relation can be derived for the effort $V_1 ds_1$ using the latter of (3) from the point of view of a polar frame of reference. Substituing $\dot{r_1}$ with the expression given by the dynamical law of the two roboticles we obtain

$$V_1 ds_1 = -dF_1 + k\frac{r_2}{\tau} dr_1 + \omega_0 {r_1}^2 d\varphi_1$$

and, then,

$$M\frac{dr_1}{r_1} + mE_1 d\varphi_1 = V_1 ds_1 + dF_1$$

We are now in condition to depict the autopoietic loop for one interacting vehicle as shown by fig. 1 where the subscripts have been omitted for the sake of clarity. It should be compared with the autopoietic loop of a single isolated vehicle reported by fig. 2. The difference is given by the terms $Md\varphi$ and $M\frac{dr}{r}$ representing the former, the perceptual perturbation due to the stigmergy of the twin vehicle, and the latter, the stigmergy delivered to the same vehicle.

As a final remark, it should be noticed that the two isolated autopoietic loops are linked together by two different oriented arcs which represent how stigmergy is exchanged between vehicles. They maintain an outer autopoietic loop which is responsible of their cooperation and, for the sake of clarity, it has been also depicted in fig. 6.

Such a control arrangement reveals the structure of a complex dynamical open system where the component parts organize themselves to better resist to the disturbance of external gradients which, in the case of the example, are issued by the mismatch between the real and the abstract environment.

V. Conclusions

In this paper we have tried to understand how *stigmergy* works as primary mechanism to maintain collective behaviors and how to borrow its implementation from ethology. To this aim we have devised robot interaction by appropriate energy exchanging between roboticle autopoietic loops. The discussion has been addressed by assuming the dissipative function of the multirobot system to be augmented with a number of specified *connective functions*, one for each pair of interacting individuals.

An important role of our investigation has been played by the mobility, which is one of the basic assumption of the roboticle model. Within this perspective, also trajectory covering can be considered an intelligent activity such as mobiligence would suggest. In our approach, however, we have tried to take the point of view of the dynamical system approach with the aim to get better insights by comparing artificial and natural systems.

As a last remark, in the discussed example of the twin followers, we have shown the relationship between autopoietic loop and macroparameters, an implementation schema we have used many times in our preceding works to make emerging collective behaviors in a robotic team.

VI. Acknowledgement

The present work has been supported partially by the Minister for Education and Research (MURST Certamen Project), by the Italian National Council of Research (CNR Special Project), and by the Italian Energy Agency (ENEA Parallel Computing Project).

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