A New Spring Net Approach to Distributed Problem Solving in Multi-Agent Systems

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Abstract

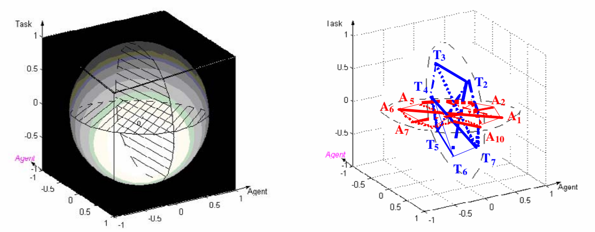
This paper presents a new spring net approach for distributed problem solving in MAS, which is entirely different from the EN for TSP and can describe a variety of complicated social interactive behavior and autonomy of agents. The simulations of task allocation and resource assignment have shown the advantages of the proposed spring net approach for distributed problem solving in MAS.

1. The Architecture of Crossbar Composite Spring Net

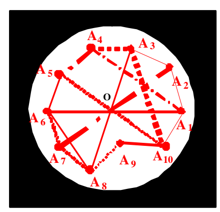
The architecture of crossbar composite spring net is illustrated in Fig.1

The horizontal spring net is composed of the nodes and springs, which represent the service agents and their social interactions, respectively. Each service node is exerted simultaneously by the gravitational field of the circumference, and by the forces that represent the interactions with other service agent nodes, with moving along the radial orbit being allowed. The distance from a service agent node to the circle center is proportional to the personal profit acquired by the agent under the current situation of MAS.

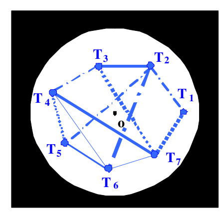
As for the vertical spring net corresponding to task agents, there is the similar organization as the horizontal spring net for service agents. But the distance from a task agent node to the center of the circumference in a vertical plane is inversely proportional to the payoff offered by the task agent for the unit resource vector required by it. There is no direct connection between the horizontal and vertical spring nets; however, they will exercise the influence on each other through the market pricing strategy.



(a) Crossbar composite spring net (CCSN)



(b) Horizontal spring-net



(c) Vertical spring-net

(A circle button represents an agent node; Black square with hollow circumference represents the gravitational field; A solid line, broken line and dash line represent a compression spring, extension spring and unilateral spring, respectively. The thickness of a line represents the strength of the spring force.)

Fig.1. The architecture of a crossbar composite spring net for task allocation and resource assignment in MAS(n=10, m=7).

2. Problem Model for MAS

Without loss of generality, from now on we will only discuss the problem-solving related to the parallel distributed task allocation and resource assignment in MAS.

The task allocation and resource assignment in MAS can be formalized by a matrix Λ, as shown in Table 1.

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There are a finite set $\mathcal{A} = \{A_1, \cdots, A_n\}$ of n service agents, and a finite set $\mathcal{T} = \{T_i, \cdots, T_m\}$ of m task agents, with each service agent A_i having a resource vector $\mathbf{r}_i = [\ r_{ik}(t)\ ]_{1\times h}$, and each task agent T_j requiring a resource vector $\mathbf{d}_j = [\ d_{jk}(t)\ ]_{1\times h}$ and having the maximally allowable payoff capacity c_j. In the meanwhile, the service agent A_i provides the task agent T_j with a resource vector $\mathbf{a}_{ij} = [\ a_{ijk}(t)\ ]_{1\times h}$, and the task agent T_j offers a payoff vector $\mathbf{p}_{ij} = [\ p_{ijk}(t)\ ]_{1\times h}$ for a unit resource vector to the service agent A_i.

Table 1 The matrix Λ representation of task allocation and resource assignment in MAS

Service Agent \ Task Agent	T_1	$\cdots$	T_j	$\cdots$	T_m
A_1	$\mathbf{a_{11}}, \mathbf{p_{11}}$	$\cdots$	$\mathbf{a_{1j}}, \mathbf{p_{1j}}$	$\cdots$	$\mathbf{a_{1m}}, \mathbf{p_{1m}}$
$\vdots$	$\vdots$		$\vdots$		$\vdots$
A_i	$\mathbf{a_{i1}}, \mathbf{p_{i1}}$	$\cdots$	$\mathbf{a_{ij}}, \mathbf{p_{ij}}$	$\cdots$	$\mathbf{a_{im}}, \mathbf{p_{im}}$
$\vdots$	$\vdots$		$\vdots$		$\vdots$
A_n	$\mathbf{a_{n1}}, \mathbf{p_{n1}}$	$\cdots$	$\mathbf{a_{nj}}, \mathbf{p_{nj}}$	$\cdots$	$\mathbf{a_{nm}}, \mathbf{p_{nm}}$

3. Crossbar Spring Net Algorithm

3.1. Evolution of Horizontal Spring Net

Given the service agent set $\mathcal{A}$ and task agent set $\mathcal{T}$, let f_i be the radial distances from the service agent node $A_i \in \mathcal{A}$ to the circumference of the gravitational field in the horizontal spring net. As mentioned in the above section, the smaller the profit acquired by the service agent A_i, the larger the value of f_i will be. Thus for the agent node A_i, we define f_i by

$$f_i = exp\ [\ -\sum_{j=1}^{m} \mathbf{a}_{ij}\mathbf{p}_{ij}^T\ ]. \tag{1}$$

The potential energy of gravitational field is defined by:

$$E_G = k^2 \ln \sum_{i=1, A_i\in\mathcal{A}}^{n} \Phi(f_i, k) \tag{2}$$

where $\Phi(f_i, k) = \exp[f_i^2/2k^2]$, and $0 \le k \le 1$.

In order to embody the effect of the interaction of A_j with respect to A_i at the time t, for the corresponding spring force that the agent node A_j exerts on the agent node A_i, we define two potential energy functions: $E_{ij}^i(f_i, f_j)$ for A_i and $E_{ij}^j(f_i, f_j)$ for A_j, respectively. We thus have the following results:

- The signs of $E_{ij}^i(f_i, f_j)$ and $E_{ij}^j(f_i, f_j)$ depend on the kind of interaction of A_j with respect to A_i, e.g. for the competition, both will be positive; and for the cooperation negative.
- The stronger the strength of interaction of A_j with respect to A_i, the larger the absolute values of $E_{ij}^i(f_i, f_j)$ and $E_{ij}^j(f_i, f_j)$. Generally, $E_{ij}^i(f_i, f_j)$ and $E_{ij}^j(f_i, f_j)$ are time-varying non-linear functions of the profits of f_i and f_j.
- The following potential energy functions Eq.(3) and (4) are defined for the spring with a linear force-deformation characterization, whereas Eq.(5) and (6) are for the spring with a non-linearly saturated force-deformation characterization, where $0 \le\ \mu_{ij}^i,\ \mu_{ij}^j\ \le 1$ are the elastic coefficients.

$$E_{ij}^i(f_i, f_j) = \pm\tfrac{1}{2}\mu_{ij}^i(f_i + f_j)^2, \tag{3}$$

$$E_{ij}^j(f_i, f_j) = \pm\tfrac{1}{2}\mu_{ij}^j(f_i + f_j)^2, \tag{4}$$

$$E_{ij}^i(f_i, f_j) = \pm\int_0^{f_i+f_j}(1 - \exp(-\mu_{ij}^i\ x))dx. \tag{5}$$

$$E_{ij}^j(f_i, f_j) = \pm\int_0^{f_i+f_j}(1 - \exp(-\mu_{ij}^j\ x))dx. \tag{6}$$

If $\mu_{ij}^i\ \neq\ \mu_{ji}^j$, then the spring forces exerted on A_i and A_j, respectively, are not symmetric, although both of them are brought about by an interaction of A_j with respect to A_j.

- In general, there are $E_{ij}^i(f_i, f_j) \neq E_{ij}^j(f_i, f_j)$, $E_{ij}^i(f_i, f_j) \neq E_{ji}^i(f_j, f_i)$, and $E_{ij}^j(f_i, f_j) \neq E_{ji}^j(f_j, f_i)$. Particularly, the unilateral interaction of A_j with respect to A_i can give rise to $E_{ij}^i(f_i, f_j) = 0$ or $E_{ij}^j(f_i, f_j) = 0$. For example, the enticement or deception behavior of A_j with respect to A_i will cause $E_{ij}^i(f_i, f_j) > 0$ and $E_{ij}^j(f_i, f_j) = 0$; the avoidance or forbearance behavior of A_j with respect to A_i will cause $E_{ij}^i(f_i, f_j) = 0$ and $E_{ij}^j(f_i, f_j) > 0$.

The global utility function J_h of the horizontal spring net is defined by:

$$J_h = \alpha\sum_{i=1}^{n} f_i + \beta_1\sum_{i=1}^{n} \parallel \sum_{j=1}^{m}\mathbf{a}_{ij} - \mathbf{r}_i \parallel^2 + \beta_2\sum_{j=1}^{m} \parallel \sum_{i=1}^{n}\mathbf{a}_{ij} - \mathbf{d}_j \parallel^2 . \tag{7}$$

where α, β_1, β_2 are positive constant.

In summary, a service agent node A_i will move along a stipulated radial orbit under the influence of the following factors:

- the personal utility f_i of A_i;
- the global utility function J_h of the horizontal spring net;
- the potential energy function E_G of the gravitational field of circumference;
- the potential energy functions $E_{ij}^i(f_i, f_j)$ and $E_{ji}^i(f_j, f_i), j \in \{1, \cdots, n\}$ of the spring forces that represent the interactions with other agent nodes.

Upon the degree of the intension for the above respective factors, distinct agents will exhibit different degree of autonomy and rationality. Therefore, the agent A_i will change its offering resource vector $\mathbf{a}_{ij}$ by the equation

$$\begin{aligned}\triangle\mathbf{a}_{ij} &= -\tau_{ij}\frac{\partial f_i}{\partial\mathbf{a}_{ij}} - \lambda_{ij}\frac{\partial E_G}{\partial\mathbf{a}_{ij}} - \rho_{ij}\frac{dJ_h}{d\mathbf{a}_{ij}} - \zeta_{ij}\frac{\partial\sum_{q=1}^{n}E_{iq}}{\partial\mathbf{a}_{ij}} \\ &= \tau_{ij}f_i\mathbf{p}_{ij} - \lambda_{ij}\frac{\partial E_G}{\partial f_i}\frac{\partial f_i}{\partial\mathbf{a}_{ij}} - \rho_{ij}[\frac{\partial J}{\partial f_i}\frac{\partial f_i}{\partial\mathbf{a}_{ij}} + \frac{\partial J_h}{\partial\mathbf{a}_{ij}}] \\ &\quad -\zeta_{ij}\frac{\partial\sum_{q=1}^{n}E_{iq}}{\partial f_i}\frac{\partial f_i}{\partial\mathbf{a}_{ij}}\end{aligned}$$

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$$= \tau_{ij} f_i \mathbf{p}_{ij} + \lambda_{ij}\omega_i f_i^2 \mathbf{p}_{ij}$$
$$+\rho_{ij}[\ \alpha f_i \mathbf{p}_{ij} - 2\beta_1 \parallel \sum_{j=1}^{m} \mathbf{a}_{ij} - \mathbf{r}_i \parallel$$
$$-2\beta_2 \parallel \sum_{i=1}^{n} \mathbf{a}_{ij} - \mathbf{d}_j \parallel] + \zeta_{ij} f_i \mathbf{p}_{ij} \frac{\partial \sum_{q=1}^{n} E_{iq}}{\partial f_i} \quad (8)$$

where $\lambda_{ij},\ \tau_{ij},\ \rho_{ij},\ \zeta_{ij}$ are all the non-negative coefficients less than 1;

$E_{iq} = E_{iq}^i(f_i, f_q) + E_{qi}^i(f_q, f_i)$;

and $\omega_i = \frac{\partial E_G}{\partial f_i}/f_i = \exp(\frac{f_i^2}{2k^2})/\sum_{i=1}^{n}\exp(\frac{f_i^2}{2k^2})$.

We can therefore obtain the radial velocity of agent A_i along its radial orbit to the circumference of gravitational field by the equation

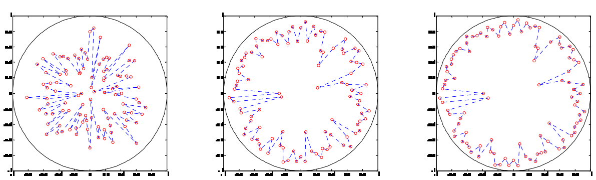
$$v_i = \frac{df_i}{dt} = \sum_{j=1}^{m} \frac{\partial f_i}{\partial \mathbf{a}_{ij}} \frac{d\mathbf{a}_{ij}^T}{dt} = -f_i \sum_{j=1}^{m} \frac{d\mathbf{a}_{ij}}{dt} \mathbf{p}_{ij}^T$$
$$\approx -f_i \sum_{j=1}^{m} \triangle \mathbf{a}_{ij} \mathbf{p}_{ij}^T \quad (9)$$

3.2. Evolution of Vertical Spring Net

Evolution of vertical composite spring net is similar to the evolution of horizontal composite spring net.

4. Simulations and Experimental

In order to investigate the performance of the crossbar composite spring net approach, we have experimented by solving 300 different problems associated to the task allocation and resource assignment in MAS.



(a)time $t_1 = 1$ (b)time $t_1 = 75$ (c)time $t_1 = 150$

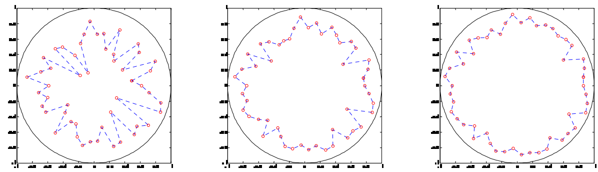
Problem Class: the whole resources possibly provided by service agents are more than whole demands practically required by task agents. The number of service agents : 100; The number of task agents : 50

Parameters:$k = 0.8$, $k' = 0.8$, $\alpha = 1$, $\beta_1 = 0.1$, $\beta_2 = 0.1$, $\alpha' = 1$, $\beta = 0.1$, $Z = 150$, $z_h = 0.001$, $z_v = 0.001$; and λ_{ij},λ'_{ij},τ_{ij}, τ'_{ij},ρ_{ij},ρ'_{ij}, ζ_{ij},ζ'_{ij}, u_{ij}, u'_{ij}, v_{ij}, v'_{ij} are in random within [0,1].

Fig.2 The trajectories of service agent nodes in the horizontal spring net. (the number of service agents :100)

The problems in our simulations are basically categorized into three classes in the sense that the total resources of service agents are much more than, much less than and approximately equal to the total demands of task agents, respectively. For each class of problems, we prepare 100 different data sets that are randomly generated. We also randomly select the half of these data sets as training sets to determine the parameters in the Eq. (8) of the crossbar composite spring net, and the other half as testing sets to examine the effectiveness of our algorithm.

During the process of problem solving, the evolutionary trajectories of service agent nodes in the horizontal spring net and task agent nodes in the vertical spring net are illustrated in Fig.2 and Fig.3, respectively.

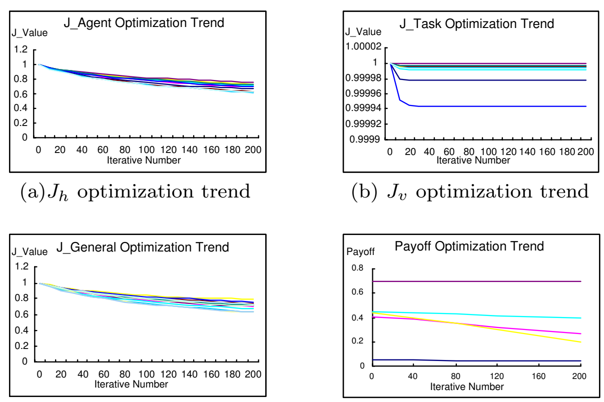


(a)time $t_1 = 1$ (b)time $t_1 = 75$ (c)time $t_1 = 150$

Problem Class: the whole resources possibly provided by service agents are more than whole demands practically required by task agents. The number of service agents : 100; The number of task agents : 50

Parameters:$k = 0.8$, $k' = 0.8$, $\alpha = 1$, $\beta_1 = 0.1$, $\beta_2 = 0.1$, $\alpha' = 1$, $\beta = 0.1$, $Z = 150$, $z_h = 0.001$, $z_v = 0.001$; and λ_{ij},λ'_{ij},τ_{ij}, τ'_{ij},ρ_{ij},ρ'_{ij}, ζ_{ij},ζ'_{ij}, u_{ij}, u'_{ij}, v_{ij}, v'_{ij} are in random within [0,1].

Fig.3 The trajectories of task agent nodes in the vertical spring net. (the number of task agent nodes :50)



(a)J_h optimization trend (b) J_v optimization trend

(c) global efficiency (d)pricing strategy

Problem Class: Supply of service agents more than Demand of task agents; The number of problems: 10, each curve for a specific problem; The number of service agents : 50; The number of task agents : 5; Parameters: $k = 0.8, k' = 0.8, \alpha = 1, \beta_1 = 0.1, \beta_2 = 0.1, \alpha' = 1, \beta = 0.1, Z = 150, z_h = 0.001, z_v = 0.001$; and $\lambda_{ij}, \lambda'_{ij}, \tau_{ij}, \tau'_{ij}, \rho_{ij}, \rho'_{ij}, \zeta_{ij}, \zeta'_{ij}, u_{ij}, u'_{ij}, v_{ij}, v'_{ij}$ are in random within [0,1].

Fig.4. The evolution of global average performance with the time elapse, depicted for 10 different problems, with each curve corresponding to a problem. (Supply $>$ Demand)

As shown in Fig.4, in the case that the total resources possibly supplied by all the service agents

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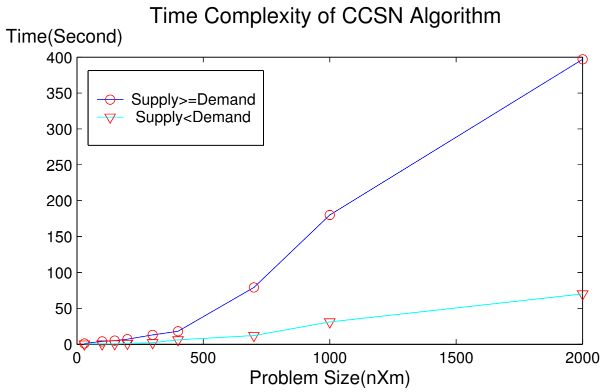
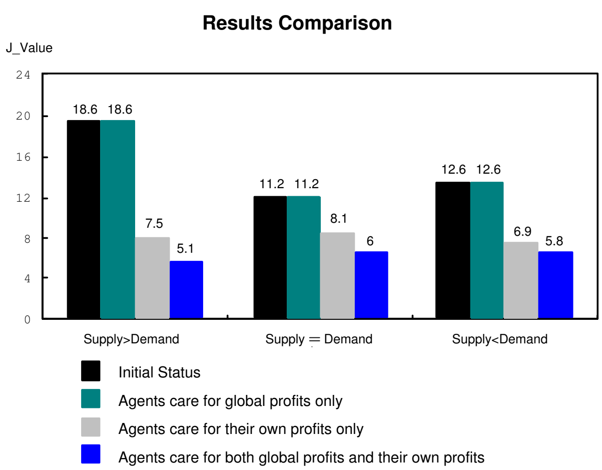
largely surpass the total demands required by all the task agents, the task agent nodes will rapidly arrive their equilibrium positions in the vertical spring net such that their requests are fully satisfied with a comparatively lower payment, whereas the service agents withstand fierce competition with each other, with a relatively longer convergence transient.



Problem Class: Parameters:$k = 0.8$, $k' = 0.8$, $\alpha = 1$, $\beta_1 = 0.1$, $\beta_2 = 0.1$, $\alpha' = 1$, $\beta = 0.1$, $Z = 200$, $z_h = 0.1$, $z_v = 0.1$; and λ_{ij}, λ'_{ij}, τ_{ij}, τ'_{ij}, ρ_{ij}, ρ'_{ij}, ζ_{ij}, ζ'_{ij}, u_{ij}, u'_{ij}, v_{ij}, v'_{ij} are in random within [0,1]; The number of problems: more than 100; Computing environment: CPU: P4 2.5G, Memory: 256M, OS: Windows2000, Tools: VC6.0

Fig.5. The time complexity with respect to the problem size $n \times m$, by using the crossbar composite spring net for the task allocation and resource assignment in MAS.



Problem Class: Parameters:$k = 0.8$, $k' = 0.8$, $\alpha = 1$, $\beta_1 = 0.1$, $\beta_2 = 0.1$, $\alpha' = 1$, $\beta = 0.1$, $Z = 200$, $z_h = 0.1$, $z_v = 0.1$; and λ_{ij}, λ'_{ij}, τ_{ij}, τ'_{ij}, ρ_{ij}, ρ'_{ij}, ζ_{ij}, ζ'_{ij}, u_{ij}, u'_{ij}, v_{ij}, v'_{ij} are in random within [0,1]; The number of problems: more than 100; This figure shows the results of 3 typical problems

Fig.6. The results comparison with respect to different Agents' selfish degree.

Under the balanced condition of the supply and demand, using the crossbar composite spring net for the problem of distributed task allocation and resource assignment in MAS will result in the time complexity with respect to the problem size $n \times m$, as shown in Fig.5. The Fig.6 clearly highlight the influence of agents' selfishness on the performance of MAS, where different selfish degree of an agent also represents in a sense its autonomous degree.

5. Conclusion

The crossbar composite spring net approach to distributed problem-solving in MAS is essentially different from the conventional elastic net and other methods currently used in MAS$[1-6]$.The proposed approach can:

- very high parallelism and real-time computational performance;
- An agent in MAS is regarded neither as being fully selfish nor as being fully unselfish. In this sense, distinct agents can also exhibit quite different autonomous degrees.
- A variety of complicated social interactions among agents can be taken into account in the process of problem-solving.
- The microscopic characterization of an individual agent can be combined with the macroscopic property of MAS.

The analysis and simulations on the task allocation and resource assignment have shown the advantages of the proposed spring net approach for distributed problem solving in MAS in terms of the parallelism and extensive suitability for the complicated environment.

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