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# Network Rewiring by Matching Automaton: from Unit Reliability to Collective Survivability

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***Abstract***: Collective intelligence of a group of intelligent robots can be realized as autonomous distributed robots with an advent of sensor network. Collective survivability can also be regarded as a subject of group problem solving, and realized by a framework of network rewiring (dynamic configuration) of systems. To realize the network rewiring, separation of physical systems and information systems is proposed to apply the self-rewiring network as well as self-repairing and self-recognition networks. Self-rewiring algorithm can be formalized as a matching automaton. An application to autonomous distributed satellites will be discussed.

***Keywords***: Network rewiring, rearrangement system, collective survivability, matching problem, dynamic configu ration.

## 1 INTRODUCTION

Network rewiring has been studied extensively in the new field of network science (e.g. [1, 2, 3]). Indeed, we can find network rewiring in many large-scale networks in nature: biological networks such as genetic networks; artificial networks such as the Internet; and social networks such as relation by birth or marriage.

On the other hand, current technology realizes highly reliable systems based on system reliability engineering using redundant components. However, the reliabilities of artificial systems are far behind from that of biological systems due to the different design principle. Biological systems involve rearrangement of similar and replaceable components when some important components fails or are missing.

As target areas for applications, group robotics where autonomous robots (agents) cooperate with each other in a framework of autonomous distributed network would be a potential area, since collective survivability is a sort of a group problem solving. The similar approach can be used for group satellite systems where small-sized but autonomous satellites cooperate with each other to increase the collective survivability for a given mission.

This paper proposes a design for autonomous distributed systems that allows rearrangement of autonomous components (agents) thus realizing high survivability rather than high reliability. The design incorporates network rewiring by matching automaton [4, 5].

Section 2 briefly surveys matching problems including stable marriage problem and stable roommate problems. Section 3 defines matching automaton based on the matching problems. Section 4 presents a design principle of separating physical and information systems to attain rearrangement system by network rewiring. A paradigm shift from unit reliability to group survivability will be discussed in several potential applications.

## 2 MATCHING PROBLEMS

The *Stable Roommates Problem* (*SRP*) [6] assumes $2N$ participants, each of whom has a strict (without tie) ordered preference over the other $2N\text{-}1$ participants. The *SRP* seeks complete matching consisting of $N$ pairs without being blocked. A matching is said to be blocked if a participant A prefer the participant C to the current roommate B in the matching and that preferred participant C also prefers A to the current partner D in the matching. The pair A-C is called as blocking pair.

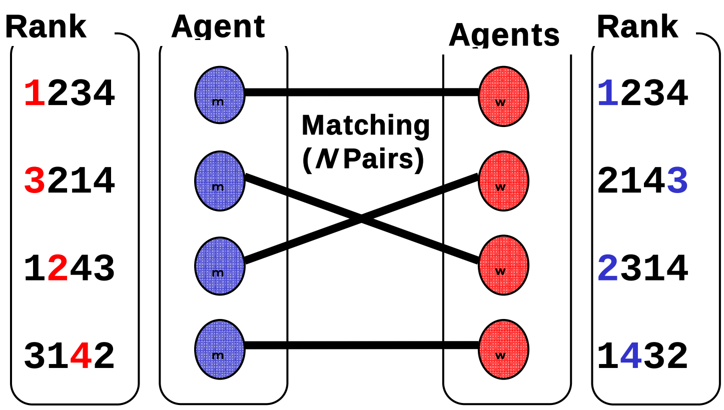


**Fig. 1.** An example of *SMP* instance specified by ordered preferences of men (left) and women (right) over the subscript of the member of the opposite sex. A bipartite graph shows a matching of *SMP* consisting of four pairs [9].

The *Stable Marriage Problem* (*SMP*) [7, 8, 9] assumes $N$ women and $N$ men, each of whom has a strict (without tie) ordered preference over the opposite sex. As in the example shown in Fig. 1, the man $m_2$ has a ranking (3, 2, 1, 4), which means that $m_2$ likes $w_3$ best, and prefers $w_3$ to $w_2$, $w_2$ to $w_1$, and $w_1$ to $w_4$.

The *SMP* seeks complete matching which satisfies *stability*. The stability requires the concept of *blocking pairs*. Two pairs ($m_i$, $w_p$) and ($m_j$, $w_q$) are blocked by the pair ($m_i$, $w_q$) if $m_i$ prefers $w_q$ to $w_p$ and $w_q$ prefers $m_i$ to $m_j$. A complete matching without being blocked is called *stable* matching.

## 3 MATCHING AUTOMATON

Structure functions [10] to express the structure of system reliability and survival functions to evaluate a time to failure [11] have been used in system reliability theory for design and assessment of reliable systems. Similarly to the structural function used in system reliability, matching automaton [4, 5] will be used in collective survivability for design and assessment of survivable systems.

The matching automaton consists of two parts of $N$ agents (automata) corresponding to men and women in the SMP. The preference is considered to be the input to the automata, and the resulting matching. In the interactive mode, the already determined pairs as well as the preference can be input to the agents whose pairs are to be determined, and that determined pair in turn can be the input to the rest of the agents, and so on.

The preference of each agent is expressed by a preference matrix { $a_{ij}$ } where the element $a_{ij}$ in the $i^{th}$ row and $j^{th}$ column is defined to be $R(m_i, w_j)/R(w_j, m_i)$ where $R(m_i, w_j)$ is the rank of $m_i$ to $w_j$.

We will use the affinity matrix $\{A(m_i, w_j)/A(w_j, m_i)\}$ to specify the matching automaton. $A(m_i, w_j)$ is the man $m_i$'s affinity for the woman $w_j$, and $A(w_j, m_i)$ is the woman $w_j$'s affinity for the man $m_i$. The affinity is defined by the rank as: $A(m_i, w_j) = N + 1 - R(m_i, w_j)$, varying from $N$ to 1 as the rank changes from 1 to $N$. In the following, the left matrix is the preference matrix and the right one is the affinity matrix of the example shown in Fig. 1. We will use the affinity matrix in the rest of the paper.

| | |
|---|---|
| 4/4,3/3,2/3,1/4 | 1/1,2/2,3/2,4/1 |
| 2/3,3/4,4/2,1/1 | 3/2,2/1,1/3,4/4 |
| 4/2,3/1,1/4,2/2 | 1/3,2/4,4/1,3/3 |
| 2/1,4/2,1/1,3/3 | 3/4,1/3,4/4,2/2 |

The cyclic preference can be generated by shifting one digit in the ordered list of 1, 2, 3, ..., $N$ where $N$ is the number of agents for one part.

For convenience of visualizing asymmetry and symmetry, the diagram is expressed on a coordinate system where women's satisfaction $H_w$ and men's satisfaction $H_m$ are defined as follows:

$$H_w(\mu) = \sum_{(w_j, m_i)\in\mu} A(w_j, m_i),$$
$$H_m(\mu) = \sum_{(w_j, m_i)\in\mu} A(m_i, w_j)$$

$A(w_j, m_i)$ is the woman $w_j$'s affinity when the mating ($w_j$, $m_i$) is attained in a matching $\mu$. All the possible matchings are plotted in the coordinate system of $H_w$ on the vertical axis and $H_m$ on the horizontal axis.

The matching automaton can be regarded as a discrete analog of a continuous dynamical model. In fact, Fig. 2 is called as *affinity space diagram*, and is similar to a *phase space diagram* which is often drawn for the continuous dynamical model where a stable matching (red node) corresponds to a stable equilibrium point (or an *attractor*) and the state proceeds to the stable matching as the exchange proceeds from an initial matching.

Since the matching automaton is a collection of automatons (similarly to cellular automatons) by identifying each agent as an automaton, the diagram of course can be regarded as a *state-transition diagram* where each node (corresponding to matching) represents a state and each edge represents a transition to and from by exchanging partners in two pairs.

As an illustration, let us explain the simplest matching automaton of a switching gate. The gate consists of two by two agents (*SMP* with size 2) and each agent in a set has a distinct preference to avoid symmetry; furthermore, each pair of agents has no first rank assignment (no *mutual infatuation*) to avoid fixation of the pair in matching. These restrictions lead to the following affinity matrix: 2/1, 1/2
1/2, 2/1.

With this preference as input, the behavior of the matching automaton is grasped by the affinity space diagram (Fig. 2). Note that only two matchings exist and both of them are stable. When the automaton seeks the women-optimal solution, then the matching will be the one on the upper left. On the other hand, if the automaton seeks the men-optimal solution, the matching will be switched to the one on the lower right.

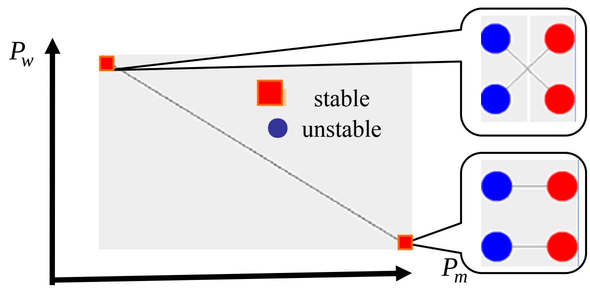


**Fig. 2.** An example of a switching gate realized by the matching automaton of 2 by 2 agents. Two squares indicate stable matchings. The matchings will be switched among one another by changing the mode of automaton, i.e., women-optimal or men-optimal [4].

## 4 NETWORK REWIRING BY MATCHING AUTOMATON

### 4.1 Separation of Physical Systems and Information Systems

Network-rewiring or rearrangement studied by matching automaton [4, 5] may be comparable to the network-rewiring by preferential rewiring in bipartite graph [12].

Network rewiring system by Matching Automaton can be applied to autonomous distributed systems such as a group of swarm robots and a group of networked satellites. Each robot (called $\boldsymbol{A_i}$, for the abbreviation of an agent *i*), for example, may be divided into two subsystems: physical system (called $\boldsymbol{P_i}$ for the agent *i*) including mechanical system, sensor system, and actuator system; and information system (called $\boldsymbol{I_i}$ for the agent *i*) including control and communication system from and to the sensor and actuator system.

Usually, in each agent $\boldsymbol{A_i}$, the information system $\boldsymbol{I_i}$ takes care of its own physical system $\boldsymbol{P_i}$, thus forming a disconnected independent nodes of $\boldsymbol{A_i}$. However, the remarkable feature of the network rewiring system is that $\boldsymbol{I_i}$ can take care of $\boldsymbol{P_j}$ ($i \neq j$), thus the network topology can be connected nodes of $\boldsymbol{A_i}$. In case of the failure of $\boldsymbol{P_i}$, $\boldsymbol{P_j}$ ($i \neq j$) can be used instead, and likewise in case of the failure of $\boldsymbol{I_i}$, $\boldsymbol{I_j}$ ($i \neq j$) can be used, thus attaining high survivability for the target tasks or the target missions. The rewiring can be used not only for collective survivability but also high robustness and high space/time resolution in sensory functions. The rewiring can be done by the Matching Automata if the preference between two sets $\{\boldsymbol{P_i}\}$ and $\{\boldsymbol{I_i}\}$ is determined considering the factors such as distances between the agents and the affinity among agents.

Matching automata is also used to evaluate the survivability of a given systems: two sets $\{\boldsymbol{P_i}\}$ and $\{\boldsymbol{I_i}\}$, and the preference between these two sets. If physical components $\boldsymbol{P_i}$ are equally important for the given mission, the preference (or affinity) from $\{\boldsymbol{I_i}\}$ should be distributed over all the $\boldsymbol{P_i}$ equally, otherwise (if the preference is biased toward one or few physical components) missing or malfunction of the preferred components would cause low preference (affinity) pair in any of rearrangements.

### 4.2 Application to Autonomous Networked Satellites

Recent advances in sensor network technology as well as collective intelligence robotics technology allows that these agents can be realized and used in the Space, that is "Sensor Net on the Space" and "Collective Intelligence on the Space" is technologically possible by small sized but ICT intensive satellites.

The framework of network rewiring by MA may be used in AntSat (AntSats, Autonomous Networked Tiny Satellites) project that aims a group of small satellites of mutually cooperative and controllable. Although sensing capability a single satellite may be limited, the space-time resolution of sensing will be greatly enhanced when a group of satellites cooperates with each other. Importantly, the survivability of a group of satellites will exceed that (reliability) of a single satellite when mutual repair and control are possible. This is true for a long term and a long distance mission demonstrated by Hayabusa [13]. Although CubeSat [14] also uses small size satellites, it does not assume Inter-satellites Corporation.

Whenever, some of the functions are disabled or failed, equal or similar functions will be enabled by rearrangement of the physical systems or the information systems. Again, the separation of physical systems and information systems will make the rearrangement possible.

Separation of physical systems and information systems allows not only rearrangement for collective survivability but also mutual repair and mutual recognition among autonomous satellites using a self-repairing network [15] and a self-recognition network [16]. For example, the self-recognition network formed by three sensors possibly from three satellites allows higher reliable prediction of High-energy Electron Flux at Geostationary Orbit [17] (Fig. 3).

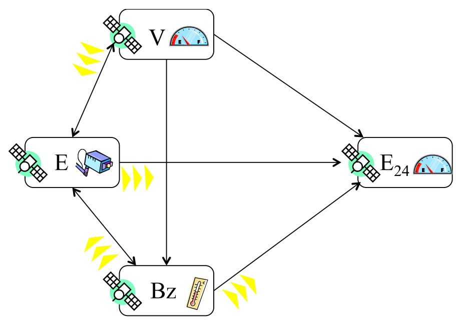


Fig.3. Mutual recognition network to predict High-energy Electron Flux at Geostationary Orbit [17]

The mutual recognition can be formed in a hierarchical system involving intra-satellite sensor systems as well as inter-satellite sensor systems (Fig. 4).

Similarly to the mutual recognition network, a mutual repair network can be formed among information systems (for the repair of information systems where repair may be carried out by mutual copying [14]) and among physical systems involving actuators that physically repair physical systems.

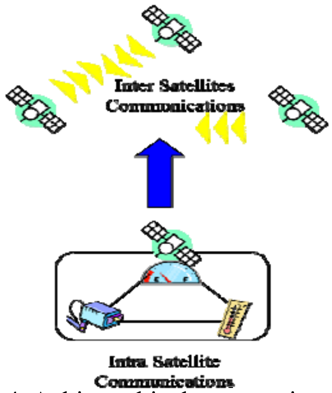


Fig. 4. A hierarchical system involving intra-satellite sensor systems as well as inter-satellite sensor svstems.

### 4.3 Application to Formation of Sister Cities

As another avenue of network-rewiring application, disaster management may be worth mentioning. The following is basically a pairing, and matching automaton based on SRP as well as SMP can be used. First, we notice that the pairing of cities (or local governments) to provide mutual support in the case of natural disaster turned out to be effective as demonstrated after the Sichuan earthquake on 12 May, 2008 in China, and it is suggested that the policy could be implemented to support the recovery of the area damaged by the Tohoku earthquake on 11 March, 2011 in Japan. To set up the situation as a matching problem, preference may be carefully designed for disaster management and support. For, example, two cities close to each other would be damaged simultaneously by a large-scale natural disaster. To support and temporarily substitute the local industry specific to the city, the paired city should have a similar industrial structure. Thus, if we first want to separate cities that could be damaged by a disaster, we use MA of bipartite structure (as in SMP), as the west part and the east part in Japan. This is similar to separation of physical systems and information systems, but differs from it that a set of agents is divided into two, rather than dividing each agent.

If are separation is neither necessary nor inadequate, MA of single connected structure (as in SRM) may be used. The preference information required for each agent will be almost doubled though.

## 5 SUMMARY

Self-rewiring network is proposed to realize dynamic and functional rearrangement of components for collective survivability as well as collective sensing.

To realize self-active networks (self-rewiring, self-repairing, and self-recognition), a design principle of a separation of information systems from physical systems in each agent is adopted. Since the collective survivability may be applied to severe missions demonstrated by the Hayabusa project, an application to autonomous networked satellites has been briefly mentioned.

"Sensor network in the space" and "collective intelligence in the space" would be a technologically sound first step.

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