322 効率的な群れ形成のための移動ロボットネットワークの設計

Design of Mobile Robot Network for Efficient Flocking

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When controlling a massively large number of mobile agents, the scalability to the number of the agents is one of the important issues. In this paper, we consider it as the motion control of flock in which a small number of leaders which know a goal navigate a large number of followers which do not. The follower determines its motion only interacting with geometrical neighbors. When we need more agents, the framework allows us to simply add followers with no adjustment or tuning, if the leaders navigate all the followers. In this paper, we analyze and discuss the flock control capacity by the leaders.

Key Words: Flocking, Swarm, Multi-agent system, Boids

本論文の目的は、非常に多数のロボットを目的地へと導く群れ制御の実現である。ここで課題となるのが、ロボットの台数に関するスケーラビリティである。ロボットの台数が多い場合、目的地の変更があったときに、それを各ロボットに伝達するのは高い時間的・通信的コストが必要になる。本論文ではこの問題を、少数の目的地を知っているリーダーが、大多数の目的地を知らないフォロワに影響を与えながら、群れ全体として目的地に移動していくことにより解決を図る。フォロワは地理的近傍のエージェントとのみ相互作用し、それ自身の移動方向を決めるとする。一方リーダーは、実際には単一のリーダーと複数のサブリーダーから構成され、これらの間では長距離の通信が可能であるとする。このような枠組みにより、群れ全体にリーダーの運動が反映され、サブリーダーとフォロワから構成される群れ全体が目的地に導かれる。移動中に目的地が変更されても、それは自然に群れ全体に伝播することが期待され、また動作中にフォロワエージェント数が増えたとしても、何一つ変更することなく動作し続けることが可能である。つまり、前述のスケーラビリティが実現される。

このような枠組みでの中心課題は、リーダーの影響を素早く群れ全体に伝えるネットワーク構造の構築と、リーダーのフォロワへの影響速度の解析である。単一リーダーと複数フォロワによる群れは、フォロワ数が増大するといくつかの断片に分離してしまい、群れ全体として目的地へ移動することができない。これは、リーダーの運動情報をエージェントが形成するネットワーク全体に伝播するスピードが遅いために起きていた。本論文では、Fig. A1 に示されるようなサブリーダーを導入することにより、エージェント数が増えても制御可能となった。

それでは、群れ全体を制御に必要なサブリーダー数はいくつになるのだろうか。様々な条件で実験を行うことにより調査した。例えば、Fig. A2 はエージェント数が 200 でサブリーダーを 25%にしたときのシミュレーション画面であり、このときは群れ全体を目的地へと導くことが可能であった。Fig. A3 にエージェント数が 150 で、サブリーダー数が増えたときの群れ全体にリーダーの速度が伝搬するまでの時間を示す。サブリーダーが増加するにつれ群れ全体への伝搬は速くなるが、全体の 25%程度でも十分短くなることがわかった。一方、自然界の生物においても、群れにおいて目的地を知っている個体数は全体の 10 から

20%程度という報告もあり、本手法での結果とよく合致している。

Fig. A1: Flock control by leader-subleader-follower

Fig.A2 Simulation snapshot

Fig.A3 Change of spread speed by subleader agent

1. INTRODUCTION

Flock is the form of lot of local interaction agent. In nature, we can watch a flock of bird, fish, bee, and so on. If we can make a flock artificially, there are various applications. For example, if we assign a task to each agent (or robot) of the flock, we can handle a task for a wide area [1] [2]. And application to Unmanned Vehicles [3] and the Surveillance Task [4] is studied. In [5], features are carried. Reynolds suggested the generation model of a flock first in 1986 [6] [7]. This model applies three following rules to each local communicating agent:

Separation : Rule with the avoidance of a collision with the neighborhood agent.

Cohesion : Rule that is going to go to the center of gravity of the neighborhood agent.

Alignment : Rule that is going to match with the speed of the neighborhood agent.

He showed that a flock was generated only in this simple rule. Aoyagi *et al.* analyzed the emergence mechanism of the Reynolds model [8]. They suggested a mathematical and quantitative index of emergence in Reynolds model. Olfati-Saber elucidated flocking mechanism by crowds as a network of the agents [9, 10]. By improving a Reynolds model, they provided a theoretical framework for design and analysis of distributed flocking algorithms for multi-agent networked systems. Kurabayashi *et al.* suggest group movement algorithm of mobile robot group in an obstacle space [11].

In this paper, we suggest the flock control method when expanding the size of flock. Suppose 2-dimensional plane without an obstacle. For control, we introduce a *Leader-Follower Strategy*. If we can control a flock by instructions to one leader agent, promotion of efficiency of the flock control is possible. In this model, only a leader agent knows a destination (or user-controllable agent), and a follower agent decides each movement by the neighbor agent. However, when there are only few leaders for a lot of followers, the flock separates and the leaders cannot control it. Because even if the speed of the leader changes, there are few agents doing the same change. We focus on "the number of agents observing a leader agent in the flock"

Fig.1 The 3 rules of Reynolds Flocking Model

and suggest a new agent that can change the number. In this paper, we use Reynolds model [6].

An outline of this paper is as follows: Flocking Control Model using Leader-Follower Strategy is explained in Section 2. Problems and Analysis of the Flocking Control Method are showed in Section 3. Proposal Method is suggested in Section 4. Simulation Results are showed in Section 5. Finally, Conclusion and Future work are explained in Section 6.

2. CONVENTIONAL FLOCKING CONTROL METHOD

In this section, we explain the flocking control method by one leader agent. We use Reynolds model as algorithm to generate a flock. And we use Leader-Follower Strategy as algorithm to control a flock. In this paper, we aim for moving a flock to the destination by instructions to the leader

A. Flocking Method

Reynolds Model emerge a flock action by communicating local interaction agents and the agent makes a network. Each agent calculates influence power from the agent in the field of vision. The power is calculated by 3 rules (Fig.1):

1) Separation Rules

This is the sum of the repulsive force not to get too close to the neighbor agents. It is in inverse proportion to square of the distance.

$$F_{Si} = -k_s \sum_{j \in N_i} \frac{x_j - x_i}{d_{j-i}^2} \quad (1)$$

where F_{Si} is the power of the separation of the i -th agent, k_s is a separation coefficient, N_i is the set of neighbor agents of i -th agent, x is a position, and d_{j-i} is the distance $\|x_j - x_i\|$.

2) Cohesion Rules

This is the sum of the gravitation not to be too far from the neighbor agents. It is a power toward a center of gravity of the flock.

$$F_{Ci} = k_c \frac{d_{ig}}{d_i} \quad (2)$$

where F_{Ci} is the power of the cohesion of the i -th agent, k_c is a cohesion coefficient, d_{ig} is the position of the center of gravity of the i -th neighbor agents, and d_i is the distance $\|d_{ig}\|$.

3) Alignment Rules

This is the power to the average velocity of the neighbor agents.

$$F_{Ai} = k_a \sum_{j \in N_i} (v_j - v_i) \quad (3)$$

where F_{Ai} is the power of the alignment of the i -th agent, k_a is a alignment coefficient, v_j is the velocity of the neighbor agents, and v_i is the velocity if the i -th agent.

The coefficients are important. The coefficients decide the form of the flock. In this study, the coefficients are following: $k_s=1.0$, $k_c=2.0$ and $k_a=4.0$.

Separation rule and Cohesion rule of the power are regarded as a rule to maintain a flock state. Furthermore, Alignment rule is regarded as a rule about the agreement of the agent speed.

The following expressions determine the movement of each agent:

$$\mathbf{F}(t) = \mathbf{F}_S(t) + \mathbf{F}_C(t) + \mathbf{F}_A(t) \quad (4)$$

$$\mathbf{a}(t) = \mathbf{F}(t)/m \quad (5)$$

$$\mathbf{v}(t+1) = \mathbf{v}(t) + kDt \cdot \mathbf{a}(t) \quad (6)$$

where $\mathbf{F}(t)$ is the sum of power of the agent, $\mathbf{a}(t)$ is the acceleration, m is the mass, $\mathbf{v}(t)$ is the velocity, and kDt is time per 1 step. In this study, mass and kDt are following: $m=1.0$, $kDt=0.01\text{sec}$ and $\text{size of field of view}=2.0$. The initial position of each agent is posted at random. However, we think about movement when a flock became a steady state in this study.

Define steady state:

- 1) All agents are connected. (The state that there is a network between arbitrary agents)
- 2) The flock can maintain the connection state.

B. Leader-Follower Strategy

Leader-Follower Strategy is the hierarchy structure that the speed of the Leader agent is handed down to Follower agents. Leader agent is an agent that user gives instructions and the agent does not communicate with other agents. In this study, Leader is an agent moving to the destination. User appoints a destination. The destination is dynamic. Follower agent is an agent obeys three rules of Reynolds Model. The Agent is regarded as an agent handling each assigned task while maintaining a flock state. In this Model, Follower agents observing a Leader agent cannot recognize a Leader agent to be a Leader agent. Table 1 show the difference of each flocking model. Long-range communication agent is a Follower agent can observe Leader agent. In Olfati-saber Model [9], All Follower agents observe Leader agent. In Kurabayashi *et al.* Model [11] and this article model (without Sub-Leader in Section 4), Leader agent is observed only in the Follower agents near the Leader agent.

Define a problem to argue by this paper:

Given: 1 Leader agent, n Follower agent (m Follower agent can

Fig.2 Reynolds Model with Leader-Follower Strategy
(1 Leader agent / 30 Follower agents)

RED-Point is the destination, RED-Agent is a leader, and BLACK-agents are follower agents

observe Leader agent anywhere). Follower agents consist of m long-range communication agents and $(n-m)$ short-range communication agents.

Find: The network that Follower agents accords at speed of Leader agent by short time enough.

Subject to: Minimize m . n (size) is fixed.

3. ANALYSIS OF THIS MODEL

In the model of Section 2, if there is much number of the agents of the flock ($n>100$), the influence of the Leader agent becomes weak and cannot control the flock. Define the following to analyze this problem:

A. Network Topology and Consensus Protocol

Network Topology is a communication network formed of Reynolds Model in Section 2. In this model, this network topology is uncertainty. However, this network has a spatial limit (Fig.3). In Olfati-Saber Model, this network topology becomes a set of a lattice. Consensus Protocol is an Alignment rule in

TABLE 1
DIFFERENCE OF EACH MODEL

Model Name	The number of Leader	The number of Follower	The number of Long-range communication agents	Formation type of the flock (Network Topology)
Reynolds Model	0	n	0	Uncertainty
Olfati-saber Model	1 (gamma-agent)	n (alpha-agent)	n	Lattice (alpha-lattice)
Kurabayashi Model	1	n	0	Lattice
This Article Model (without Sub-Leader)	1	n	0	Uncertainty
This Article Model (with Sub-Leader)	1	n	$m (< n)$	Uncertainty

Fig.3 Network topology of Flocking Model

Fig.4 Example of Response Time
(In this case, Response Time is about 2500steps.)

Reynolds Model. In the Alignment rule, the rule increases a difference of the speed as power. In this analysis, we only use Network Topology and Consensus Protocol.

B. Response Time (steps)

Response Time is the time when average velocity of Follower agents in the flock became same as velocity of a Leader agent. In this analysis, the initial velocity of Follower agents are 0.0, the initial velocity of Leader agent is 0.0, the terminal velocity of Leader agent is 4.0, and the acceleration of Leader agent is 0.2. In Fig.4 (sample), Response Time is about 2500 steps.

C. Percentage of Leader-Degree (%)

Percentage of Leader-Degree is a numerical ratio of Follower agents observing a Leader agent.

Percentage of LeaderDegree

$$= \frac{\text{the number of agents observing a leader agent}}{\text{the number of agents in the flock}} \times 100 \quad (7)$$

Fig.5 shows Response Time and Percentage of Leader-Degree in small flocks ($n=10, 20, 30, 40, 50$). Response Time depends on Percentage of Leader-Degree not only the position of the Leader agent and the size of the flock. When Percentage of Leader-Degree is big, Response Time decreases.

Fig.5 Response Time and Percentage of LeaderDegree in small flock ($n=10, 20, 30, 40, 50$)

Fig.1 The 3 rules of Reynolds Flocking Model

4. PROPOSAL METHOD

In this section, we suggest the model that added the new type agent (Sub-Leader) to Leader-Follower Strategy. The Sub-Leader agent is Long-range communication Follower agent. This agent can observe a Leader agent anywhere. Fig.6 shows new hierarchical structure. Table 2 is the difference of agent type. "To add Sub-Leader agent" is that Follower agent is promoted to Sub-Leader agent (Fig.7). We inspected the flocking control model including Sub-Leader agent. Fig.8 shows the result adding Sub-Leader agents. The number of agents in the flock is 150. Five network samples are displayed. From the result, we find that Response Time is improved. The left edge expresses Response Time of the flock without Sub-Leader agent. And the right edge expresses Response Time of the flock that all follower agents became Sub-Leader agents. When all Follower agents become Sub-Leader agents, Response Time is shortest. However, when Percentage is little (about 20%), Response Time is short enough.

5. SIMULATION RESULTS

We found that Response Time is improved in section IV. In this section, we show evaluation by the simulation of the proposal method. The number of agents in the flock is 200. The

Fig.7 To add sub-leader agent
(to make a follower agent chosen at random a sub-leader agent)

result is Fig.9. Fig.9(a) is the movement of the flock without Sub-Leader agent. In this case, the Follower agents do not follow the movement of the Leader agent. This is the problem. If the speed that the velocity of the Leader agent spreads out is slow, the alignment power of change of Leader agent becomes weak. And the flock separates. (Because a simulation filed is a torus, the flock comes out of the bottom.)

Fig.9(b) is the movement of the flock that all Follower agents became Sub-Leader agents. This case resembles Olfati-Saber Model. We can control the flock, because Response Time is short. However, there are too many long-range communicating agents. Fig.9(c) is the movement of the flock that 25% Sub-Leader agent case. This case also can control the flock. And there are few agents of the long-range communication.

6. CONCLUSIONS

In this paper, we focus on the problem of flocking control model and suggested the solution method (expanded Leader-Follower Strategy). There is a limit by the size for the control of the flock by 1 Leader agent. It is thought that this problem includes even other models. The proposal method can change "the number of the Follower agents observing a Leader agent" (Sub-Leader agent). In the simulation, we did movement evaluation by the number of Sub-Leader agents. When the flock agents increase, Response Time is improved by the introduction of the Sub-Leader agent. When all agents observed a Leader agent, Response Time was shortest. However, flocking control in 25% Sub-Leader case is enough. We think about an applica-

Fig.8 Response time adding sub-leader agent
(n=150, 1 leader agent / 150 sub-leader agent
and follower agents)

TABLE 2
DIFFERENCE OF AGENT TYPE

Agent Type	Field of Vision (Interaction Range)	Power
Leader	None	0
Sub-Leader	Local and Long-Range(Leader)	$FS+FC+FA$
Follower	Local	$FS+FC+FA$

tion to the other models, an implementation method to the actual machine or robot in future.

APPENDIX

Degree Distribution Fig.8 shows the difference of each model. The network of this article model is different from other model. When we think about velocity consensus, the network topology is important. The Degree Distribution of this article mode and Olfati-Saber model are following:

This Article Model (Reynolds Model with Leader)

Olfati-Saber Model (Alpha Agents)

(a) No Sub-Leader case, 1 Leader agent / 0 Sub-Leader agents / 200 Follower agents

(b) All Sub-Leader case, 1 Leader agent / 200 Sub-Leader agents / 0 Follower agents

(c) 25% Sub-Leader case, 1 Leader agent / 50 Sub-Leader agents / 150 Follower agents

Fig.9 Simulation result

Time →

The y-axis (numbers) is a degree. The x-axis is a node. In this article model, each agent permits plural agents in the field of vision, but a degree is limited (to form a lattice) in Olfati-Saber model.

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