A Study of Emergent Computation of Life-Like Behavior by Indefinite Observation

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Abstract. This paper describes the action generation of an autonomous animated agent. The agent behaves as if it has subjective motivation that is affected by its experiences. A typical study of this generation uses an ad-hoc method for the subjective action because it focuses on the action selection to solve some task. This paper proposes an indefinite communication architecture (ICA) to generate a subjective action. ICA keeps the experiences of an agent using indefinite observation. In particular, since the indefinite observation gives some chaotic feature to the experience, ICA generates various actions in response to an environment. This paper simulates and discusses the behavior of ICA in our interactive system.

Keywords: Life-Like Behavior, Autonomous Agent, Indefinite Observation, Emergent Computation, Subjective Experience

1 Introduction

Recently, there has been a lot of research examining a subjective action for believable agents [6] and robot entertainment [3]. The subjective action is a response triggered by a physiological phenomena. For example, "what should a robot do if it is hungry?" or "what is best if a robot is in pain or is injured ?". This paper describes a subjective action of an autonomous animated agent. We define the word "subjective" as something existing only in an agent's internal state.

Typical studies use behavior sets [5], which are distributed representations [2] of the action to generate a subjective action. The approach[1] of Blumberg and his colleagues added Level of Interest variables to the behavior sets to handle a subjective action. The Level of Interest variables represent the strength of a subjective motivation. In addition, the variables are adjusted using a learning mechanism. However, such research [3][6] almost always deals with subjective action in an ad hoc manner.

The main problem when dealing with subjective action is to prepare a definitive tool for measuring the quality of subjective motivation. Unfortunately, there is no such a tool. However, someone may insist that this quality can be measured statistically, but statistics cannot explain why each quality emerges. People have the same problem because they cannot give an accurate report about the degree of a subjective quality with definitive descriptions in things like the report of a feeling, the quality of color, or the quality of pain. Even though a person can use various words as definite descriptions to represent the quality, these words cannot adequately assess a degree of the quality. The absence of a definitive description indicates that there is no accurate representation of a subjective quality. For example, the designer of an agent cannot represent an accurate degree of hunger or of pain. The quality of a subjective motivation also has the same difficulty in representations. Due to the representation difficulty, the designer cannot give the agent a subjective motivation as well as an action in response to the motivation. Since this fact suggests the impossibility of designing a subjective action by a tool that measures subjective qualities, a significant problem for an agent designer is how to prepare a mechanism instead of the measuring tool.

In this paper, our contribution is to show that there is a possible mechanism for generating a subjective action without the Level of Interest variables or an ad hoc implementation. The main mechanism is indefinite observation[4]. Our idea is to use indefinite observation as an emergent computation to generate a subjective action. In our approach, indefinite observation forms a contradiction between the generation and the perception of an agent's action. Since the contradiction takes apart an old standard and generates a new standard, indefinite observation has an advantage for emerging a new agent's action based on its experience.

We named the mechanism of the emergent computation Indefinite Communication Architecture (ICA). ICA changes the quality of a subjective action according to the observation of an action contradiction. The action generated by ICA is in contrast to the one generated by ordinary systems that use the selection of behavior. In particular, the action of ICA depends more on a subjective experience of an agent than an ordinary system using a learning mechanism. This is because the subjective experiences immediately affect the action generation through an observation log.

In this paper, ICA gives a subjective action to an autonomous mobile agent like that in figure 1. An example in the virtual world is the process where the agents and a user gather at one place to have their photographs taken. This virtual world appears in the interactive system, we developed, FurintClub. The agent behaves in the virtual world affected by its subjective motivation like real people. For example, many actions emerge when real people gather in a place. A person may stop to go forward in spite of the fact that there is more space between him and other people. A person may or may not also proceed much closer to others in response to their movement. The motivation of these movements is in the subjective point of view because the decision of the movement depends on a single person's experiences. FurintClub provides such a subjective motivation

Fig. 1. Snapshot of user and autonomous agents in FurintClub

to agents by using ICA.

We hope that ICA can generate lifelike behavior, which sometime obeys a rule and sometimes does not. Moreover, this research tries to make a model of emergent computation as the origin of lifelike behavior.

In this paper, we introduce an interactive system FurintClub. In section 2, we give formal descriptions for the experience-based action of an agent and the goal of the spontaneous generation of an action standard in the virtual world. We propose an Indefinite Communication Architecture crucial for the generation of an agent's action in section 3, and show an example of an interaction between a user and these agents in section 4. We evaluate our architecture in section 5 with simulation of an agent's behavior that is generated by ICA. Finally, we conclude this paper and discuss the problems of ICA in section 6.

2 Interactive System FurintClub

Figure 2 shows the structure of the interactive system FurintClub. FurintClub consists of Pfinder[7][1] and a CG generator. Pfinder is used to track a user in front of the display, and the user can interact with an agent in the virtual world. When the user moves toward the left or the right in the real world, an avator of the user moves in the virtual world with the same movements.

The action of gathering or the arrangement of agents for the photograph emerges from an interaction in FurintClub. The response to a user is not a static one like an ordinary behavior set defined prior to the interaction. The response action is based on an agent's experiences. Since the experiences of agents vary, the actions of each agent differ from each other. As a result, the user is attracted

[1] Pfinder is a vision system developed at MIT media labs. This system can find a person from the camera view point.

Fig. 2. Structure of FurintClub

to the movements of the agent, which responds to the user in a different way. Moreover, the user feels that the agent has a kind of subjective motivation.

2.1 Experience-Based Action of Autonomous Agent

An agent takes an experience-based action. Figure 3 indicates the structure of an action generation mechanism for the autonomous agent. The structure has three components: a perception, a generation, and a context. The perception part perceives an action generated by other agents as well as the action of itself. The generation part generates an action for the agent according to the results of the perception. The context part gives a standard for the perception to judge an action and for the generation to generate an action. Moreover, the contents of the context are also generated by the perception. In short, the context is based on the experience of each agent. Therefore, we call the action generated by these components an experienced-based action. We explain, in section 2.2, the reason why the generation of context must depend on the perception.

There are two movement features of an agent in the virtual world: the speed V of the agent and an angle Θ (the direction the agent proceeds). A representation of the movement is a pair of the feature F and a value X: (F, X). For example, when an agent moves at a speed of 10, the representation is $(V, 10)$. A user's movement is also represented in the same form.

We formalize the experience-based action in terms of the perception and the generation. The perception part is defined in the following function:

$$\phi_o(X_F) = True\ or\ False, \phi_o \in O(F, C), \tag{1}$$

where $O(F, C)$ is a set of a function ϕ_o, which observes a movement X_F of a feature F according to a judgment standard C. The function ϕ_o returns a truth-value according to a perception standard C. For example, under the standard of speed $C : 5 < x < 10$, the function decides that the speed of an agent $X_V = 2$ is false.

Fig. 3. Action generation mechanism of autonomous agent.

The generation part is defined in the following function:

$$\phi_g(T) = X_F, \phi_g \in G(F, X), \tag{2}$$

where $G(F, X)$ is a set of a function ϕ_g which gives an agent a movement X of feature F. T is a truth-value generated from a result of the perception. For example, in $\phi_g \in G(V, 10)$ and $T = True$, the agent's speed is given a value of 10.

We must prepare a rule for a goal before formalizing ICA. The following rule represents the goals rule that gives an agent a subjective action,

$$X_{other} \rightarrow C, X. \tag{3}$$

Here, X_{other} is the variable that does not fit in the standards. The rule means that the action generation mechanism obtains a new action standard C, X in the function (1), (2) from the movement X_{other} of the other agent.

2.2 Indefinite Observation

The implementation of rule 3 is crucial for providing an agent with a subjective experience. The origin of the rule is indefinite observation [4]. Indefinite observation is proposed to explain the subjective behavior of a creature. It suggests that a subjective behavior emerges from an observation and a generation. The function generating the subjective behavior comes from the results of the action observation. For example, when a person divides oranges into two groups like big or small, he/she will do according to his/her experiences gained through past divisions. In the example, the action of the division develops a standard by dividing an orange, and people also divide it according to an acquired standard; however, in comparison, a computer divides oranges firmly based on a threshold value given by a programmer prior to the division.

There are some chaotic features based on an observation slip in the process of indefinite observation like the example of oranges. The slip is attributed to an observer. The observer of an indefinite observation has a local viewpoint of a behavior. Since a local observer cannot immediately perceive all of the world or the behavior himself, the slip occurs between experiences and actions[2]. Rule 3 emulates such a observation slip by adding X_{other} to the standards C, X.

3 Indefinite Communication Architecture

ICA observes the actions of its own agent and of the two nearest agents (or a user), and generates an action according to the observation. The function between the observation and the generation of the action is defined in the following form:

$$F(a_1, a_2, a_3) \rightarrow m. \tag{4}$$

Here, $a_i, m = \{True\ or\ False\}$. a_1 and a_3 represent the results of the observations of the nearest agents' movements, and a_2 is also the result of ICA's own movements. In another notation, a_i forms an equation $\phi_o(A_i) = a_i$ by function (1) where A_i is a movement of an agent i, and m in function (4) is input to the action generation. As a result of function (2), the equation between m and A_i is $\phi_g(m) = A_i$.

ICA has the following features to realize a subjective behavior:

- "Indefinite observation", which makes an agent's action similar to the another agent.
- "Order generation function", which produces an original action for the agent.

Although indefinite observation results in rule (3), there is lack of a spontaneous aspect when generating a behavior. The order generation function provides the agent with the spontaneous aspect.

Indefinite observation incorporates a movement observed as false into a standard of perception C and generation X in some probability. In short, putting X_{other} in its standards, this observation carries out rule (3) in some probability. Since the indefinite observation adapts the standards to the movements of others, the actions of the agents become similar to each other.

An order generation function F is function (4) itself, which controls the order of the action generation $\phi_g(m)$. In the process of an action generation, if $m = True$, then $\phi_g(m) = A_i$. If $m = False$, then $\phi_g(m) = \neg A_i$. $\neg A_i$ indicates an action that does not exist in an action generation standard X. Since $\neg A_i$ generates an action outside of the standard, it prevents the movements of agents from becoming similar to each other.

Figure 4 indicates the ICA structure of agent A2. There are two agents A1 and A3 near agent A2. The ICA structure of A2 is also shown at the top of the figure.

A perception (observation) part, a generation part of an action, and a context part are on the left-side, on the right-side , and in the middle at the

[2] Since there are many parameters in complex system, an observer cannot completely detect the parameters related to an event in finite time.

Fig. 4. ICA structure of agent A2

top of figure 4, respectively. The perception observes the three actions of agents A1, A2, and A3, and gives the result of the observation to the order function. The order function decides the order of an action and gives the result to the generation. The generation generates an action A_2 according to the order from the order function, and gives the action A_2 to agent A2.

The context is a table which consists of several movement values (F, X). The context's contents develop through the observation of the perception. The perception ϕ_o writes down an observed action (F, X) in the context when it judges that the action is true. For example, when $X_v = 2$ and $\phi_o(2) = True$, the perception writes down the value $(V, 2)$ in the context. According to the change of the context, both standard C and X get close to the value $(V, 2)$. Here, the standard of judgment C is made from inequalities of the maximum and minimum value of the context, and the standard of generation X is selected from the context at random. The more the perception perceives the same value, the more the contents of the context approach the value.

3.1 Contribution of Indefinite Observation

Indefinite observation contributes to the development of a subjective experience with the contradiction of an observation because the contradiction performs rule (3), which adds X_{other} to the standards C and X. Since the perception adds a value judged as true to the context, the result of the perception must come to

Fig. 5. Order function usage and reproduction

the same thing as $\phi_o(X_{other}) = True$ to add X_{other}. However, since X_{other} does not suit the standard C, the actual result is $\phi_o(X_{other}) = False$. ICA uses the contradiction of the observation to turn the judgment of $\phi_o(X_{other})$ into true. For example, when the speed of an agent is 4 and the standard of the perception is $C : 5 < x < 10$, the indefinite observation decides that speed 4 is true. The standard changes to $C : 4 < x < 10$ after the observation.

ICA uses the contradiction in some probability. The contents become an agent's own experiences because the probable observation is a unique experience to each agent. This is reason why we uses the word "subjective" for an agent's experience.

3.2 Contribution of Order Function

Order function contributes to the adaptation of the degree of spontaneity for an agent's behavior. The degree means how often generated actions depend on the context. The more the action depends on a context, the more it becomes ordered. In contrast, when the action depends less on a context, it becomes disordered. The dependency on the context occurs when a true value is given to the generation part ϕ_g. Since the output value of the order function is given to the generation part ϕ_g, the degree of spontaneity is arranged by the ratio of a true value to a false one in output values of the order function.

ICA spontaneously generates the output values of order function (m in function 4). Figure 5 shows the outline of usage and reproduction of the order function. The order function consists of a table (order function table), which suggests a relation between the inputs and outputs of the function. In this table, 1 indicates a true value and 0 a false value. The order function is given input values from the perception part ϕ_o. Then, it seeks an output value appropriate for the input values and gives the generation part ϕ_g its value.

There are two functions that are opposite to each other in reproducing the order function: one makes an agent's behavior depend on a context when the behaviors of near agents become disordered; the other makes the behavior disordered when the behaviors of near agents depend on the context of the agent. The ordered behavior means that the agent has a behavior similar to the other agents' behaviors according to indefinite observation. The disordered behavior means that the agent has a spontaneous behavior. The order function can adapt the degree of behavioral spontaneity with these two functions.

Although we described the conditions for choosing the two reproduction functions, ICA does not actually have the conditions. It only spontaneously reproduces the order function table using indefinite observation. The advantage of the spontaneous reproduction is that it does not need any evaluation function for good or bad behavior. The reproduction is only based on the context of an agent. The value of a behavior emerges from the context, not from an evaluation function given by the designer.

The reproduction of the order function contains some complicated processes by indefinite observation. This reproduction uses the perception part ϕ_o to reproduce the output value of the order function. In figure 5, the arrow with the comment "reproduce" indicates the reproduction process with perception part ϕ_o. The perception part judges the new action $A2$ just produced by the generation part, and replaces the output value in the order function table with the judgment result of the new $A2$.

The judgment result of the new $A2$ is sometimes not equal to the value m given to the generation part $\phi_g(m)$ to produce a new $A2$. This is because the context used by the reproduction is sometimes different from that used by the generation when producing a new $A2$. There are two mechanisms connected with this contextual difference. The first mechanism is where the generation part uses the same context used by the perception part when observing the old $A2$, $A1$, and $A3$. The second mechanism is where the perception part of the reproduction uses the same context generated by the observation part when observing the old $A2$, $A1$, and $A3$. Since indefinite observation sometimes makes the context vary before and after the observation of the old $A2$, $A1$, and $A3$, the difference of context occurs between the generation in generating a new $A2$ and the perception in observing a new $A2$ for reproduction.

As a result, the reproduction process has the ability to adjust the ratio of a true value to a false one in the order function table. If the behavior of the near agents, $A1$ and $A3$, depends on the context of agent A2, the reproduction process increases the ratio of a false value on the order function table. Since the context of A2 is restricted to the same behavior as the other agent's under this condition, the context is very sensitive to strange behavior. It is easy for the context to change with indefinite observation when observing strange behavior. Once the context changes, a false value increases in the order function table. If the agent's behavior becomes disordered, the reproduction process increases the ratio of true values on the order function table. Since indefinite observation adapts the context for the spontaneous action, the reproduction process increases

Fig. 6. Independent movement agent

the ratio of true values on the order function table with the new context.

3.3 Task of Taking Photographs

ICA gives constraints to the context part for the agents when they gather to have their photographs taken. There are two constraints: one is where an agent turns in the direction of the user, and the other is where the agent near the user turns in the direction of the camera[3]. Since the constraints are provided to ICA through the context, it only indirectly affects the agent's behavior. As a result, ICA can sometimes generate various actions obeying the constraints.

4 Example of Agent's Action in FurintClub

Figures 6, 7, and 8 show an example of an interaction between a user and agents.

Figure 6 shows that the agent in the black circle moved alone in the virtual world in spite of the fact that a user and two agents gathered at one place. This independent behavior occurs when the contents of the context part differ from those of other agents. The difference is a result of the observation part ϕ_o outputting a false value in the judgment of other agents' movements.

However, the agent that moved alone began to participate in the group (the user and two agents) according to the change in the ICA context's contents. The reason for the change in the contents is that an indefinite observation inserts the movements of the other agents into the ICA context.

The upper left side of figure 7 shows the agent on the way to join the group of the user and the agents. As a result of this participation, the agent that joined the group moves with the others like so in the upper right side of figure 7. The

[3] this is not the real camera for Pfinder.

Fig. 7. Agent participation in group and dropping out of group

contents of the context parts in the group members are similar to each other during the group behavior.

For a while, ICA generates a new type of action that does not exist in the contents of the context part because the order function inputs a false value to the action generation part ϕ_g. If indefinite observation takes the new actions into the context, its contents gradually become different from other members in the group. Such an agent drops out of the group like so in the bottom of figure 7.

When constraints for the photograph exist in the context part, the behavior for the photograph dominates the agent's movement. As a result, the agent moves in the direction of the user like so in the left side of figure 8. Furthermore, when the agent arrives at a place near the user, it turns in the direction of the camera. The two agents in the foreground of figure 6 were situated for a photograph. However, the behavior resulting from the constraints disappears according to a disassembly of the contents by the false output of the order function. As a result, the agent moves away from the user like so in the right side of figure 8.

The main factor in a series of these behaviors is a change in the relation in each agent's context. The contexts change by becoming similar or opposite to each other. Indefinite observation is the main mechanism for such similar or opposite characteristics.

Fig. 8. Agent moves toward user and away from user

5 Evaluation of ICA

5.1 Simulation of Agents

We evaluate ICA by simulating the movements of agents. Ten agents are only given a speed feature (V, v) to easily determine the properties of ICA. Hence, these agents only proceed forward. The movement speed for each agent is decided by ICA. We plot the distance of each agent from its initial position.

Moreover, we evaluate ICA by two parameters. One is λ, which is the ratio of the true value to the false value in the order function table. The range of value of λ is $0 \leq \lambda \leq 1$. The closer the value λ is to 1, the more true values exist in the context part. The other parameter is P, which is a probability of contradiction by indefinite observation. We conducted two simulations to evaluate the effect of these parameters on ICA. The first simulation examines the behavior of the context with respect to static λ by recording the average value of the contents in the context. The other simulation examines the diversity of λ with respect to static probability P.

5.2 Movements of Agents

Figure 9 represents the forward movement of the ten agents. The horizontal axis of the graph represents the simulation times. The vertical axis represents the distance of the agents' movements from their initial positions. Each line represents the movement of one agent. Figure 9 suggests that several agent groups emerged from the simulation when the agents moved forward. Between the 2000 and the 2500 step stage in the simulation, one of the agent groups sped up. Near the 4300 step stage some agents sped up and joined the other agent groups at the newly generated speed.

This simulation suggests that a group behavior emerged through mutual observation and the groups also collapsed. The groups suggest the existence of

Fig. 9. Plot of agents' movements

a stable structure of context parts between agents; the agent maintained the same speed as other agents in its group. Furthermore, the construction and deconstruction of the groups also indicates ICA's ability to produce various behaviors for a group activity.

5.3 Behavior of ICA

Figure 10 represents the diversity of a context during a simulation. In figure 10, each graph represents a different simulation in terms of λ of the order function table: in graph A, $\lambda = 0$; in B, $\lambda = 0.5$; in C, $\lambda = 0.9$; and in D, $\lambda = 1.0$. In the simulation the probability $P = 0.5$. The horizontal axis of the graph represents the simulation times, and the vertical axis represents the average of values in a context(the average speed in a context). In each graph, there are ten plots for the averages of the ten agents.

Graph A suggests that the average values diverged during the simulation. This is because when $\lambda = 0$, all inputs to the generation part ϕ_g are false, which causes ϕ_g to generate a random speed. Consequently, both the behavior and context of the agents became disordered. Conversely, graph D suggests that the average value converged during the simulation. As λ tended to 1.0, all the inputs to generation part ϕ_g tended to be true values, which caused ϕ_g to generate a speed only from a context. As a result, the context of each agent became similar through mutual observation. Graph B shows behavior between those of graphs A and D. However, we are particularly interested in graph C because it exhibits the kind of lifelike behavior in ICA that we hope to achieve. By the 1600 step stage, the average of the contexts was stable at a speed of 3.0, although some diversity could be seen in graph C. Some kind of catastrophe occurred near 1600 steps. The average of the agent's context rose to the speed of 8.0 and the two groups emerged after this catastrophe. Consequently, ICA exhibited both construction and destruction of behaviors at $\lambda = 0.9$

Fig. 10. Diversity of context in response to λ: in graph A, $\lambda = 0$; in B, $\lambda = 0.5$; in C, $\lambda = 0.9$; and in D, $\lambda = 1.0$

Figure 11 represents the diversity of λ throughout the length of the simulation. In figure 11, each graph exhibits a different simulation of probability P for an observation part ϕ_o: in graph A, $P = 0.5$; in B, $P = 0.25$; and in C, $P = 0.01$. The horizontal axis of the graph represents the simulation times and the vertical axis represents λ of each agent's order function table. In each graph, there are ten plots for each agent.

We pay particular attention to graph A because the λ of graph A has suggested values between 0.7 and 0.9. Moreover, λ approaches 0.9 from an initial value of 0.5. This property suggests that ICA with $P = 0.5$ has the capacity to recover from disorder even when ICA has lost its order of context. In the other graphs, both B and C had a wide range of values for λ. The range is far form $\lambda = 0.9$. In terms of $\lambda = 0.9$, ICA presents an unappealing property for probability P in graphs B and C.

5.4 Discussion of Simulation

Both graph C in figure 10 and graph A in figure 11 demonstrate that the context has features of stability and liquidity in its structure when $P = 0.5$. The groups of the agents appeared and collapsed like figure 9 because of the features.

The behavior of each agent does not come from an evaluation function provided by the designer. It certainly comes from the experiences of each agent.

Fig. 11. The change of λ in response to Probability P: in graph A $P = 0.5$, in B $P = 0.25$, and in C $P = 0.01$

In particular, the collapse and the appearance of the groups is different from a search for the optimum grouping. The worthiness of a behavior is estimated by the context a group keeps, and is transformed according to the collapse and the appearance of the group. Evaluation functions are unnecessary because the group has experience-based values. This is an advantage of ICA compared to other generation mechanisms of subjective behavior that use some evaluation mechanism.

6 Conclusion

This paper proposed a new action generator named ICA, where the action of an agent emerges from its calculation as if the action is a result of a subjective motivation. ICA generates an action standard by indefinite observation and order function. The action generated by ICA has two opposite features: one is an individual behavior, and the other is a group-based behavior. While the individual behavior is a result of the subjective experience of the agent by observation, the group behavior is also a result of the observation because the contents of the observation are generated in a selfish manner and are also affected by the action of the other agents. These features play a significant role for ICA in generating a subjective action.

Moreover, we constructed an interactive system, FurintClub, using ICA. The agents in FurintClub generate various actions such as an individual action, a group action, movement toward a user, and away from a user in response to the user's or another agent's movements. As a result of the various actions, FurintClub attracts the user's attention by the movement of the agents.

The action generated by the existing ICA is a very simple action such as the movement of an agent in the virtual world. For our next step, we will implement more action features in ICA to support more powerful interaction. Presently, ICA has a problem of controllability because it is still unclear as to how experience leads to some kind of an action. We have not captured such a behavioral tendency driven by the environment. Fortunately, since the experience depends on the environment, we will be able to control the behavior of ICA by giving an agent a particular environment if the tendency becomes clear. In the future, we will challenge the problem of controlling ICA with environmental parameters.

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