第一页为封面页

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Implementation of a Coalition Control System in a Fishing Model

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Abstract
In this paper, we develop a coalition control algorithm based on model predicative control(MPC) mechanism and test it using a fishing model with linear parameters. The fishing model is focusing on the problem of how to distribute fishing fleets in certain regions to get the maximum fish caught. Our algorithm is able to put individual fishing boat into coalition, and therefore increase the fishing amount by introducing cooperation between fleets. In our design, we are able to merge or split fishing boats based on the predicative information from the MPC.

Keywords: Coalition control – MPC – Game theory – Optimization

1 INTRODUCTION

A multi-agent control system needs to consider the balance between self-interest and collective interest. When we have a coupled system, there can be numerous decisions to make by each agents, and these decisions have the intentions to either maximize the self-interest or collective interest. However, when making decisions, one agent can influence the others, and it is also possible that the influence can be negative, in a way that against the agent's original intent. The contradiction lead us to the contemplation of finding the best or most profitable decision of a multi-agent system. In such system, we need to first evaluate which is more important, the individuality or the entire group, and then find an appropriate trade-off mechanism if conflict occurs. For some problems, agents can be cooperative. If that is the case, we need to consider the fact that agents can form coalition to increase its own interest and possibly the interest of the entire group at the same time. The process of finding the best coalition structure is what we called coalition control. [1]

In this paper, we use a fishing model to illustrate the idea of coalition control. The fishing model includes certain number of fishing fleets and regions. Each boat has an effort parameter that decides how much attention it pays to a certain region. Also, we include the fish inflow rate, which is the amount of fish get in from other places, and fish population survival rate, which is the amount of fish that will live after a time period. To make problem easier to implement, we set the parameters to be linear. In our design, we introduce the ideas of cross-coalition communication and no cross-coalition communication. If the agents are in a no cross-coalition communication system, the agents have no information regarding how other coalition behave, whereas in a cross-coalition system, all the information are shared. In a cross-coalition system, we design a redistribution method to determine the way of changing coalition form. If the fishing boat sees cooperation gains greater benefit, it will join with other boats. On the contrary, if the fishing boat sees better opportunity to work alone or with other boats, it jumps out the current coalition structure and forms a new one.

The method of finding most appropriate coalition structure include the knowledge of game theory. First, we introduce some principals that will guide us when designing the protocols of a multi-agent system. The first one is social optimum, and it is the condition that the sum of each agent's interest is maximized. For the social optimum solution, we do not need to let the agent know the decisions from other agents, but we find the best solution from the perspective of the entire group.[2] The second one is Nash-bargaining solution, and in this case, the agents communicate with each other frequently. During the communication, one agent is able to find its best interest after judging the information from the surroundings. In the end, no one's interest can be further increased, and equilibrium is therefore established.[3][4]

We also utilize a handy tool while designing the coalition structure in the fishing problem. The tool is called model predicative control(MPC), and as the name suggests, it gives a predictive result of a certain model. MPC is used when we have a function, and we would like to see how the function runs in a given time horizon. It is possible for us to set the boundary conditions so the function can approach the desired direction. In total, MPC is a solver that can optimize objective function with constraints. In our design, we use MPC to give each boat the capability of predicting the future and find the best strategy at the current time step. In other words, MPC tells the captain whether to merge with other boats to form coalition or not if greater benefits can be achieved. The MPC solver is implemented in the MATLAB toolbox and we take it as part of our design. [5]

2 THEORY

2.1 Problem Statement

We consider the following game theoretical set-up. We assume that there are N regions where a fishing boat can invest time in fishing. These are identified with the set of numbers $\mathcal{N} := \{1, 2, ..., N\}$. We initially assume that populations of fish in the i-th region, denoted by $x_i(t)$ evolve according to a linear equation of the following kind:

$$x_i(t+1) = A_i + B_i x_i(t), \tag{1}$$

in the absence of fishing boats. Notice that A_i is a constant inflow of fish, while B_i represent the survival rate of the population. This is a very simplistic model but still allows us to capture some of the trade-offs involved in coordinating multiple fishing boats. If the geographical distribution of the regions is known and one wants to take into account the ability of fish to move from one region to another, diffusive coupling could be added to the equations.

There are K fishing boats operating in the N regions and each boat $k \in \mathcal{K} := \{1, 2, ..., K\}$ will decide the effort to be devoted at fishing in the region i at time t, denoted by $e_{k,i}(t)$. It is assumed that each boat will extract from the corresponding region an amount of fish proportional to the effort $e_{k,i}(t)$ and to the amount of fish $x_i(t)$ in the corresponding region. In particular then, the evolution of fish can be modeled as:

$$x_i(t+1) = A_i + B_i x_i(t) - \sum_k \gamma_k e_{k,i}(t) x_i(t), \tag{2}$$

where γ_k is the proportionality constant which may be different for each boat, taking into account the fact that their technologies for fishing might be more or less effcient. The case of equal k is also of interest though. Each boat k is interested in maximising his own catch:

$$O_k = \sum_t \sum_i e_{k,i}(t) x_i(t), \tag{3}$$

over a certain time interval $\{0, 1, 2, ..., T\}$ that will be used as a prediction horizon of our coalitional MPC model. The effort of each boat is supposed to be non-negative and the total effort, in the various areas needs to add-up to 1.

$$e_{k,i}(t) \geq 0, \quad \sum_i e_{k,i}(t) = 1. \tag{4}$$

Each boat is therefore able to choose where he wants to focus his fishing efforts and how to determine when and where to fish. Notice that congestion in a particular area rich of fish will deplete the area and lead to a loss of profitability in fishing in it.

Fishing boats are allowed to form coalitions. A coalition is a subset $\mathcal{C} \in \mathcal{K}$ of boats which jointly optimize their efforts to maximize the total amount of fish they can extract at see. In particular, the objective function is:

$$O_{\mathcal{C}_i} = \sum_t \sum_k \sum_i \gamma_k e_{k,i}(t) x_i(t). \tag{5}$$

Notice that a coalition could be a single boat; in which case $\mathcal{C} = \{k\}$ and consistently we see that $O_k = O_{\{k\}}$. At each time t the fleet of boats is partitioned in a number of coalitions:

$$\mathcal{K} = \mathcal{C}_1(t) \cup \mathcal{C}_2(t) \cup \ldots \cup \mathcal{C}_c(t), \tag{6}$$

where $C(t)$ is the number of coalitions at time t (which could change) and $\mathcal{C}_q(t)$denotes the q-th coalition. Each boat only belongs to a given coalition at any time t. At each time t each coalition solves the following optimisation problem of maximizing objective function $O_{\mathcal{C}}$.

2.2 Evolution Function

We assume an evolution function for $x(t)$ of the following type:

1. No cross-coalition communication: this is in the absence of information of how other coalitions are going to behave an optimistic view point is taken that their efforts are 0.
2. Cross-coalitions communication: in this case the efforts $e_{k,i}(t)$ are are fixed and a-priori communicated. This communication is done only once every time-step by broadcasting their fishing schedule to all other coalitions. The first coalition to do so will typically use the predicted schedules from the previous time instant (shifted by one and suitably complemented at the final time) in order to build his own fishing schedule. Order of communication may of course impact the final outcome.

Each coalition, moreover, will also take into account the possibility of merging with another coalition. The merge operation will only happen if both coalitions are happy about it. In particular, by carrying out an optimization of the cost function $O_{\mathcal{C}_1\cup\mathcal{C}_2}$ where $\mathcal{C}_1$ and $\mathcal{C}_2$ are the two coalitions considering a merge operation. We will consider the following two criteria to assess the convenience of a merging operation:

- With fish redistribution

$$O^*_{\mathcal{C}_1\cup C_2} \geq O^*_{\mathcal{C}_1} + O^*_{\mathcal{C}_2}, \tag{7}$$

  We denote by u^* and x^* the optimal schedule and state-solution corresponding to the merged coalition.This implies that the predicted optimal total amount of fish of the merged coalition is higher than than the sum of the fish caught by individual coalitions acting alone. It is agreed that coalition C1 will get an amount of fish equal to:

$$x_{(\mathcal{C}_1)} = O^*_{\mathcal{C}_1\cup C_2}\frac{O^*_{\mathcal{C}_1}}{O^*_{\mathcal{C}_1} + O^*_{\mathcal{C}_2}} \tag{8}$$

  and coalition $\mathcal{C}_2$ will get the amount of fish equal to:

$$x_{(\mathcal{C}_2)} = O^*_{\mathcal{C}_1\cup C_2}\frac{O^*_{\mathcal{C}_2}}{O^*_{\mathcal{C}_1} + O^*_{\mathcal{C}_2}}. \tag{9}$$

- Without fish redistribution

$$x_{(\mathcal{C}_1)} = \sum_{k\in\mathcal{C}_1}\sum_i e^*_{k,i}(t)x^*_i(t), \tag{10}$$

  A similar expression holds for $\mathcal{C}_2$. Notice that, in this case each boat inside a coalition will receive the amount of fish it catches $\sum_i e^*_{k,i}(t)x^*_i(t)$.

Once a coalition is formed which entails fish redistribution, the ratios $r1 := \frac{O^*_{\mathcal{C}_1}}{O^*_{\mathcal{C}_1}+O^*_{\mathcal{C}_2}}$ and $r2 := \frac{O^*_{\mathcal{C}_2}}{O^*_{\mathcal{C}_1}+O^*_{\mathcal{C}_2}}$ are recorded and used for subsequent attribution of the amount of fish for each coalition.

Then, the mechanisms for splitting of coalitions is similarly including individual agents split. Individual agents may decide to leave a coalition when the amount of fish they would get in prediction by being part of the coalition is less than what they would otherwise. The coalition, needs to agree a policy for redesign of the fish redistribution ratios r_i.

At each new time instant t, the coalitions coming from the previous time $t-1$, will check if merge or split operations will occur and thus decide the new coalition structure at time t. Sometimes one could argue that this operation is only carried out every T time steps or longer, to avoid coalition forming and splitting which is too fast. Once the coalition structure at the current time has been agreed, then the optimisation is carried out sequentially and optimal fishing efforts computed. Only the first one is implemente, fish stock evolve in time and the problem is reformulated at the following time instant, giving rise to a coalitional receding horizon control protocol.

3 ALGORITHM

When we consider the cross-communication system, we can make a flow chart to show how to implement the problem and advance in time. Referring to the Figure 1, we start from the node of multi-agent system. Then we choose if in this step we need to adjust the coalition structure. If yes, we use MPC to find equilibrium condition or most desired decision, and we perform the operation of merging or splitting to let the coalition structure to reach its purpose. If no, we simply employ the MPC solver to continue our current path without altering anything. The output of the system are the values of current objective function, individual interests and collective interests.

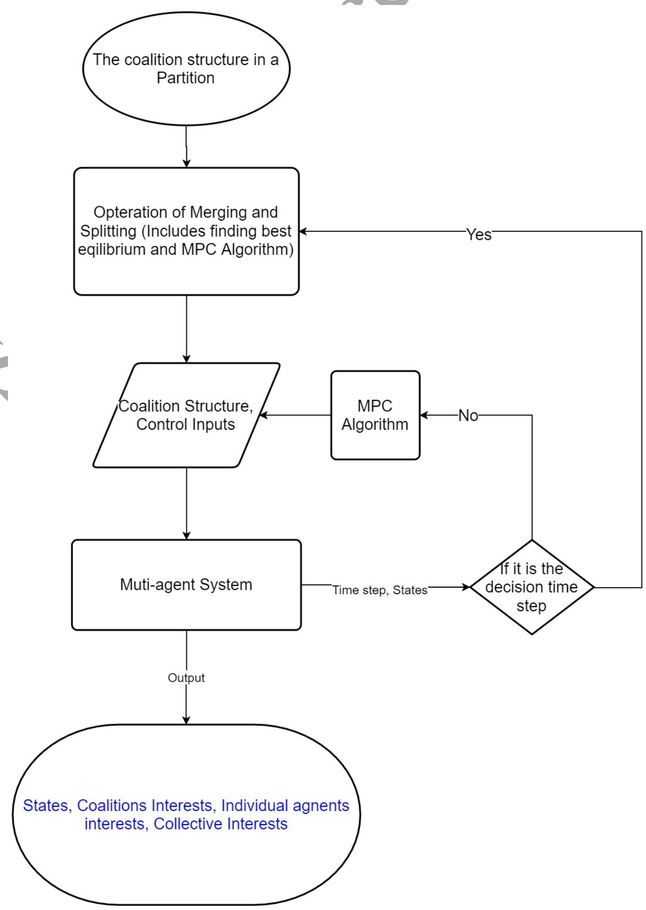

Figure 1. Flowchart of cross-coalition communication algorithm.

Next, we illustrate the pseudo-code (Figure 2) for our algorithm of updating fishing amount in region x and each boat's effort e. When implementing, we choose the input to be the current knowledge about the entire system, which include the coalition structure, fish amount in each region, current effort and predicted effort of each boat. So we have an optimisation problem to work with. In the algorithm, we solve this optimisation problem for each agent, and we update the fish amount and individual effort afterward. Notice that in the algorithm we exclude the process of MPC computation, but in fact in the nested loops we need to solve the optimisation problem using MPC and it takes great computational effort.

Input: $\{\mathcal{K} = \{\mathcal{C}_1(t), \mathcal{C}_2(t), \dots, \mathcal{C}_c(t)\}$, max_iteration, $\mathbf{x}(t)$, $\hat{\mathbf{e}}$, $\tilde{\mathbf{e}}$ and "optimal problem"

if $c>1$
    max_iteration=max_iteration;
else
    max_iteration=1;
end
$\mathbf{x}^{eq} = \mathbf{x}(t)$

for t=1 to max_iteration do
    for i=1 to c do
        $\mathcal{O}^*_{\mathcal{K}} \leftarrow$ solve optimal problem w.r.t $\tilde{\mathbf{e}}_{\mathcal{C}_i}$ and $\mathbf{x}^{eq}$ by using $\hat{\mathbf{e}}_{\mathcal{C}_i}$ $\mathbf{x}^{eq}$ as the initial guess, and **
            **the set of $\tilde{\mathbf{e}}_{(\mathcal{P}\backslash\mathcal{C}_i)}$ as the fixed value

        $\tilde{\mathbf{e}}_{\mathcal{C}_i}$ and $\hat{\mathbf{e}}_{\mathcal{C}_i} \leftarrow \mathbf{e}^*_{\mathcal{C}_i}$; $\mathbf{x}^{eq} \leftarrow \mathbf{x}^{eq*}$
    end
end

$$\mathbf{e}^{eq} = \begin{bmatrix} \tilde{\mathbf{e}}_{\mathcal{C}_1} \\ \tilde{\mathbf{e}}_{\mathcal{C}_2} \\ \vdots \\ \tilde{\mathbf{e}}_{\mathcal{C}_c} \end{bmatrix} \triangleq \begin{bmatrix} \mathbf{e}^{eq}_{\mathcal{C}_1} \\ \mathbf{e}^{eq}_{\mathcal{C}_2} \\ \vdots \\ \mathbf{e}^{eq}_{\mathcal{C}_c} \end{bmatrix}$$

Output:vector $\mathbf{e}^{eq}$, $\mathbf{x}^{eq}$

Figure 2. Pseudo-code illustration of how we update efforts vector and fish amount vector. Notice in the code that we use two loops to go through each agent in each coalition for all the time steps.

Symbol	Meaning	Value
N	number of regions	4
K	fishing fleets number	6
A_1	1st region fish inflow	300
A_2	2nd region fish inflow	450
A_3	3rd region fish inflow	350
A_4	4th region fish inflow	200
B_1	1st region survival rate	0.2
B_2	2nd region survival rate	0.3
B_3	3rd region survival rate	0.45
B_4	4th region survival rate	0.6
γ_1	1st boat capability	0.08
γ_2	2nd boat capability	0.1
γ_3	3rd boat capability	0.12
γ_4	4th boat capability	0.15
γ_5	5th boat capability	0.20
γ_6	6th boat capability	0.28
x_1^0	1st region initial fish	200
x_2^0	2nd region initial fish	300
x_3^0	3rd region initial fish	150
x_4^0	4th region initial fish	250

Table 1 Parameters we chose to use in order to make the fishing model in a way that the grand coalition is the efficient structure.

4 RESULTS

4.1 Parameters

First, we show the initial conditions being used in the paper. We construct the problem to have four fishing regions and six fishing fleets. Each region has its fish inflow rate and survival rate, which is described earlier. Also, each boat has the fishing capability factor γ so we can differentiate. The numeric values of the parameter we used are shown in the Table 1.

With the parameters set, it is easy to prove that the grand coalition, in which all fishing fleets goes into one coalition, will lead to maximum fishing caught. The obvious reason is that our model is linear and the fish inflow is very large. In other words, the fish is abundant and all fishing fleet do not need to worry too much about not catching anything. As a result, we have a reference point, so that we can compare if our result can be close to the theoretically best result. On the other hand, we can also set each boat to be in its own coalition, so that we eliminate the effect of cooperation. In this case, we decide that our coalition control method will not be allowed to converge to grand coalition, and the maximum number of agents in one coalition to be 3. We should expect the fish caught to be less than the grand coalition.

In addition, we set the total time step to be 720. If each step represents 1 day, the total fishing period is two years. Also, we decide that the fleet will make decision of merging or splitting each month, so the computation can be efficient. In other words, the coalition structure will be adjusted in 30 time steps.

4.2 Results

After we run the implemented algorithm, we have the following results. First, we show the change of coalition structure of the entire fishing fleet.

Figure 3 shows that initially boat 1 and boat 2 decide to merge and form one coalition. Then in the next month boat 3 decides to join. Next, we see that three boats split and each boat become independent. Then, the coalition structure changes with time until 150 days or 5 months. At this time, boat 2, boat 4 and boat 6 forms one coalition and the other boats decide to remain single. This coalition structure no longer changes with time, and the system, including the amount of fish in each region and the total fish caught, reaches equilibrium state.

Next, we show the amount of fish in each region in Figure 4. We observe periodic structure of fish amount in all regions. It is reasonable that once the fish in an area is depleted, fish from other places gets in quickly. From the figure, we also see that the periodic structure changes along with the change in coalition structure,

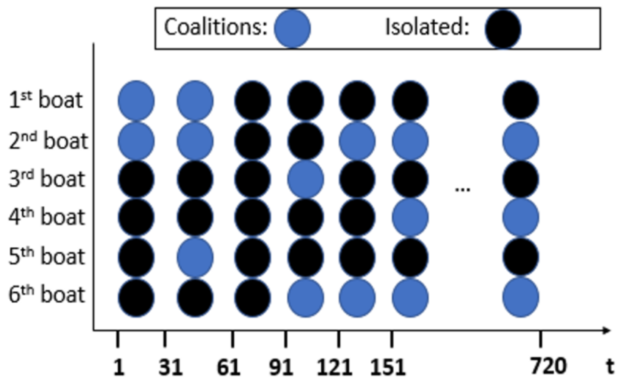

Figure 3. How coalition structure changes after each month. After 150 days, we find that the coalition structure remains the same, which suggests that the dynamic problem reaches a steady state.

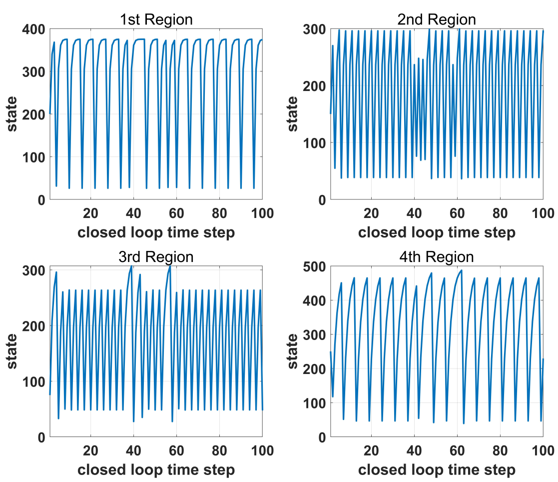

Figure 4. The amount of fish changes in each time step. We see the periodic behavior changes with the change in coalition structure.

even though the time step may not be perfectly match.

After knowing how the coalition structure and region's fish population change, we come back to the interested result of total fishing caught. Here, we list the results for the structures of grand coalition (Table 2), isolated coalition (Table 3) and controlled coalition (Table 4). We find that the result for all three coalition forms are very close, but we still observe that the grand coalition has the maximum amount of fish caught. In our coalition design, the result is very close to the result of grand coalition.

Graphically, we show the result of fish caught of 1st boat using different coalition structure in Figure 5. Still, we observe very small difference in terms of fish caught. However, we can see that the periodic structure has been changed in the two scenarios even though they seem to

Symbol	Description	Value
$\mathcal{F}$	total fish caught	337.21×10^3
$\mathcal{F}_1$	1st boat	28.51×10^3
$\mathcal{F}_2$	2nd boat	35.90×10^3
$\mathcal{F}_3$	3rd boat	43.29×10^3
$\mathcal{F}_4$	4th boat	54.35×10^3
$\mathcal{F}_5$	5th boat	72.85×10^3
$\mathcal{F}_6$	6th boat	102.31×10^3

Table 2 Grand Coaliton: The total fish caught of entire fleet and each boat in 2 years/720 time steps.

Symbol	Description	Value
$\mathcal{F}$	total fish caught	330.54×10^3
$\mathcal{F}_1$	1st boat	28.01×10^3
$\mathcal{F}_2$	2nd boat	35.42×10^3
$\mathcal{F}_3$	3rd boat	42.23×10^3
$\mathcal{F}_4$	4th boat	53.23×10^3
$\mathcal{F}_5$	5th boat	71.42×10^3
$\mathcal{F}_6$	6th boat	100.23×10^3

Table 3 Isolated Coaliton: The total fish caught of entire fleet and each boat in 2 years/720 time steps.

Symbol	Description	Value
$\mathcal{F}$	total fish caught	336.59×10^3
$\mathcal{F}_1$	1st boat	28.22×10^3
$\mathcal{F}_2$	2nd boat	35.45×10^3
$\mathcal{F}_3$	3rd boat	43.32×10^3
$\mathcal{F}_4$	4th boat	54.56×10^3
$\mathcal{F}_5$	5th boat	72.91×10^3
$\mathcal{F}_6$	6th boat	102.13×10^3

Table 4 Controlled Coaliton: The total fish caught of entire fleet and each boat in 2 years/720 time steps.

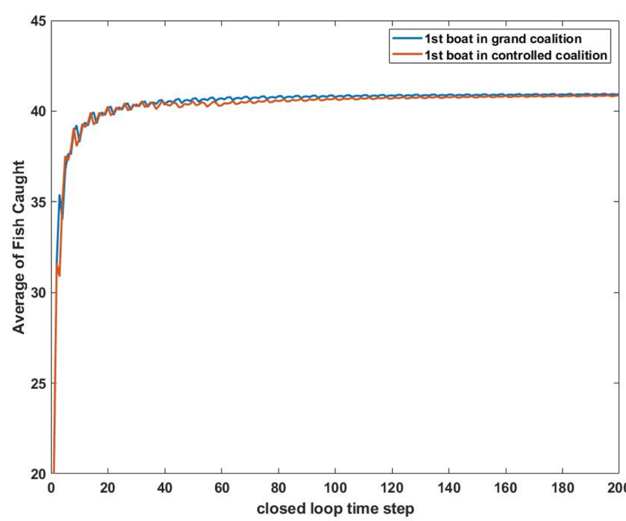

Figure 5. The comparison between grand coalition and controlled coalition of fish caught of 1st boat.

converge to the same point. The other boats display similar behaviors comparing to 1st boat.

5 CONCLUSION

From the results we show earlier, we can make the following conclusions.

1. The coalition structure finally converges to the form that the 2nd, 3rd and 6th boats are in one coalition, and the other boats are isolated.
2. The distribution of fishing boats reaches steady states after 150 time step.
3. Different input parameters changes the form of coalition. As a result, the periodic solution will be changed as well.
4. The result of our coalition control method is close to the result of grand coalition, which finds a Nash social optimum in a single coalition structure, whereas our algorithm alters coalition structure based on decisions from MPC.

In the specific fishing model, our coalitional control method has close performance comparing to grand coalition method. It suggests that our model is capable of handling more complex problems in which the self-interest needs to be considered.

To reveal the true power of our coalition control design, we will have to use more complex model for testing. For example, we can set non linear fish inflow and consumption of cooperation, so that the model will be difficult to solve. Also, in our algorithm, we rely too heavily on the result of MPC solver and it is not efficient in terms of computation power. It takes a lot of time to find the choice of merging or splitting among agents, even though it seems reasonable that future can be hard to predict.

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致谢

春去秋来，时光荏苒，如潺潺流水……

从我选题到论文完成，已经是一年多的时间了。在此期间，兴趣一直引领着我。有时我灵光乍现，向着科学的方向前行；有时我困惑不已，陷入思维的沼泽无法自拔。在此期间……我最想表达的是感谢，我的老师，父母，同学们。正是他们，不断鼓励我，鞭策我，在我困难时给我指明前进方向。

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