Application of a Mobile Robot for Picking Berries Under Qualitative Uncertainty of Conditions

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Abstract. Over the last decade, the development of computer technology has progressed significantly, which allowed to automate many production processes through the use of intelligent control systems. The possibility of creating modern control systems that allow solving complex multi-factor tasks in conditions of uncertainty has significantly expanded the scope of application of robotics. The article considers an approach to solving one of the tasks of controlling an intelligent mobile robot for agricultural purposes – selecting the order of application of the robot for picking berries. The procedure for decision-making by an intelligent control system for a mobile robot under the qualitative uncertainty of berry picking conditions has been developed. This procedure can be implemented by developing software. The approach proposed by the authors to solving such problems can be used not only for control the intelligent mobile robot for picking berries, but also for other purposes. The article presents the results of applying the developed method for solving the task of control the agricultural mobile robot for picking strawberry in the climatic conditions of Central Russia.

1. Introduction

Today, mobile robotics are widely used across almost every industry in order to solve for a number of complex tasks, such as execution heavy or long monotonous work, performing human tasks in the warehouses and industrial premises [1-6].

To control of mobile robots are actively used artificial intelligence technologies such as fuzzy logic or artificial neural and neuro-fuzzy networks. Intelligent robots are able to make decisions and select optimal actions based on sensory information about the state of the environment, including objects over which they perform certain actions [1, 6-12].

In agriculture mobile robots are used for driving various agricultural equipment, unloading, loading and distributing agricultural products in the field and in warehouses, collecting and packing finished products, sorting vegetables and fruits, conducting preparatory operations before sowing, treating crops in fields and greenhouses with pesticides, insecticides, fungicides and fertilizers [1, 13-16].

One of the most difficult to automate operations is harvesting berries. The main problems are the damage to the berries and bushes in the picking and picking of unripe berries. In addition, the
harvesting of berries is limited to the period of their ripening, which makes it impossible to pick all the berries at the same time [17-19].

Several companies are searching for solutions to this problem. Thus, the Spanish company Agrobot offers for its solution an experienced robot SW6010. It works completely offline and is able to navigate independently in space. The machine uses real-time artificial intelligence technology to assess the ripeness of berries. The robot is also equipped with sensors to assess the color of the berry and its presentation. When Agrobot SW6010 finishes picking berries in the row, it stops and passes the data to the operator. In three days, one Agrobot SW6010 can pick strawberries from 800 acres [20].

The profit of an agricultural enterprise engaged in growing strawberries depends on the weight and quality of the picked berries. The maximum profit can be obtained if absolutely all the berries are picked in a state of shipment ripeness and dry, that is, suitable for transportation with the preservation of marketable qualities. However, in the climate of Central Russia, weather conditions (periodic rains) do not allow to use each day for berry picking. In rainy weather, berry picking is usually not carried out, which reduces the weight of the harvested crop and, accordingly, the profit from its sale. In addition, after the rain, it should take a certain time for the berry to dry. Picking wet berries reduces its quality and makes it less suitable for transportation and storage. At the same time, berries that are not picked in time in rainy weather spoiled by gray rot, slugs and frogs: when picking berries one day later than their ripening, up to 30% is lost, and two days later up to 60% of the harvest is lost. In addition, the berry goes from post-shipment ripeness to full ripeness. It is possible to partially compensate for the days lost due to the rains by quickly harvesting with the help of a large number of robots, but it is not economically feasible to maintain an excessive amount of equipment. Weather conditions also affect the rate of ripening of strawberries. The long period of dry and warm weather is the ideal conditions for picking berries. But if it is sunny, dry and hot weather, then the berry ripens very quickly and the berry picking should be carried out promptly. At the same time dry weather reduces the risk of berries rotting and being eaten by slugs. Therefore, it is optimal to make rational decision how to use the available resources to maximize profits in the face of unavoidable crop losses [3, 6].

Thus, picking berries by a mobile robot can be attributed to the tasks with a low degree of organization of the external environment and insufficient a priori information about it [20-24].

2. Experimental section

2.1. Problem statement

In dry and warm weather the intelligent mobile can pick all the berries from its area of the strawberries field. But if it is not possible to collect all the berries because of the predicted rain, it can pick only the largest berries from its area of the field. It is known that the cost of large berries is about 1.5 times more than medium-sized ones and 4 times more than small ones that are processed only for canning production. But not picked during berries partially rot and will be eaten by pests [25].

Knowing the weather forecast for a certain period of time, the intelligent robot control system should estimate the time that the robot has to pick berries before the rain and the duration of rainy weather and take one of the solutions that provides the greatest profit from the harvest:

- to pick all the berries from some part of its area of the field for the available time, if it does not rain and the picking can be continued the next day;
- to pick only the best large berries, if the rain is prolonged and the picking can’t be continued a few days;
- to pick large and medium-sized berries, if the rain will go to half day or one day and then the weather will be dry and sunny [25].

The mobile robot must be equipped with a three-level intelligent control system. It should make decisions depending on the level of certainty, completeness and accuracy of information about the situation and its assessment: at the first level decisions are made on unambiguous situations, at the second - on ambiguous non-fuzzy situations, at the third - on ambiguous fuzzy situations.
Picking berries depends on weather conditions, timing and speed of ripening berries, on the weight and quality of the picked berries and some other conditions. The states of the harvest conditions are known inaccurately and, in addition, the usefulness of solutions for picking berries in different states is not accurately determined, that is, the situations that arise will be ambiguous. The decision will be made by the intelligent mobile robot control system at its third level. In this case, the most effective method is the method described in [1].

The essence of the method is as follows. It is necessary to select an alternative (option) of the solution that corresponds to the external conditions. The choice of an alternative under different environmental conditions (berry picking conditions) is characterized by different utility, the analysis of which allows to make a decision. There is $A = \{a_1, a_2, ... , a_n\} -$ the set of options, the selecting of one of which depends on the state of object (intelligent mobile robot) $X = \{x_1, x_2, ... , x_i\}$. It is known that if the $a_i$ option is selected for the state $x_i$, then its utility will be $u_o$. For various variants and possible states of the system, there is an $m\times n$ matrix of utility:

$$U = \begin{bmatrix}
    u_{11} & u_{12} & u_{1n} \\
    u_{21} & u_{22} & u_{2n} \\
    u_{m1} & u_m & u_{mn}
\end{bmatrix}$$

With a known state of the system $x_i$, the best option is the one with the greatest utility $u_o = \max_{i=1,m} u_{ij}$.

The utility associated with the $a_i$ option in the $x_i$ state is fuzzy and is given by the fuzzy set:

$$\overline{U}_{ij} = \bigcup_k \mu_{\overline{g}_{ij}}(u_k)/u_k$$

where the exact values of the fuzzy utility $U$ are $u_k \in U_1 = \{u_{ij}\}, k \in J, i \in I = \{1, m\}, j \in J = \{1, n\}$.

Then the utility matrix has the form: $= ||\overline{U}_{ij}||_{m\times n}$.

The state of the system is given and described by a fuzzy set: $\tilde{X} = \{\mu_{\tilde{g}}(x_k)/x_k\}$, $x_k \in X, k \in J$. It is required to find the best option $a_o$.

A. Algorithm of decision-making

1. To reduce fuzzy utilities $\overline{U}_i = \{\mu_{\tilde{g}}(x_k)/U_k\}$ to fuzzy sets on exact utility values. In other words, it is necessary to determine the fuzzy utilities for a given state of the system for different solutions for all $i = \overline{1,m}, k \in J$:

$$\overline{U}_i = \{\mu_{\tilde{g}}(x_k)/\overline{U}_{ik}\}$$

The calculation $\overline{U}_i$ uses a rule for calculating the algebraic sum of two fuzzy sets:

$$\mu_i(x) = (\mu_i(x)+\mu_i(x)-\mu_i(x)-\mu_i(x)) \quad \forall x \in X$$

2. To calculate $\overline{U}_i$ on the exact utilities for all $i = \overline{1,m}, k \in J$. The fuzzy set $\overline{U}_i$ consists of fuzzy subsets and can be reduced to a fuzzy set on the exact values of utility. If the element of fuzzy set $\overline{U}_i$ is $\mu_{\overline{g}_{ij}}(\overline{U}_i)/\overline{U}_i = \mu_{\overline{g}_{ij}}(\mu_{\tilde{g}_{ik}}(u_k)/u_k)/\mu_{\tilde{g}_{ik}}(u_k)/u_k)$, then the value of the membership degree of the exact value $u_k$ to the fuzzy set $\overline{U}_i$ is determined from its belonging to $\overline{U}_{ik}$ and belonging $\overline{U}_{ik}$ to $\overline{U}_i$:

$$\mu_{\overline{g}_{ij}}(u_k) = \min \{\mu_{\tilde{g}}(x_k), \mu_{\tilde{g}_{ik}}(u_k)\}$$

$$u_k \in U_1 = \{u_{ij}\}, k \in J, i \in I = \{1, m\}, j \in J = \{1, n\}$$

Where $\mu_{\overline{g}_{ij}}(u_k)/u_k$ is membership degree of the exact value $u_k$ to the fuzzy set $\overline{U}_i$, $u_k \in U_1$, $\tilde{X} = \{\mu_{\tilde{g}}(x_k)/x_k\}, x_k \in X$. 

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The calculation $\tilde{U}_i^*$ for equal $u_k$ uses a rule for calculating the algebraic sum of two fuzzy sets expressed by the formula (3).

3. To determine the maximizing sets.

The maximizing set of the function $f$ on the set $Y$ is a fuzzy set $M(f)$, such that the membership degree of some $y$ to which characterizes the proximity of $f(y)$ to $\text{sup} f$ (support $f$). Similarly, the maximizing set $M(Y)$ of the set $Y$ is a fuzzy subset whose membership degree for $y \in Y$ expresses in some sense the proximity of $y$ to $\text{sup} Y$ [23].

In our case, the set $Y$ containing all possible utility values for a given fuzzy state will have the form $Y = \bigcup_{i=1}^{m} S(\tilde{U}_{im})$ and the maximizing sets for all $i = 1, m$ are:

$$\tilde{U}_{im} = \{\mu_{\tilde{U}_m}(u_k)/u_k\}$$

where $\mu_{\tilde{U}_m}(u_k) = (u_k/u_{m,\text{max}})^d$, $u_{\text{max}} = \text{sup} Y$, $d$ is integer.

4. To determine the optimizing sets $\tilde{U}_{io}$ based on the intersection of the fuzzy sets $\tilde{U}_{im}$ and $\tilde{U}_i^*$, obtained by formulas (4) and (5):

$$\mu_{\tilde{U}_{io}}(u_k) = \min (\mu_{\tilde{U}_m}(u_k), \mu_{\tilde{U}_i^*}(u_k))$$

5. To find the set $\tilde{A}_o = \bigcup_i \mu_{\tilde{A}_o}(a_i)/a_i$ that represents the optimal solution. The membership degrees $\mu_{\tilde{A}_o}(a_i)$ are determined by the formula:

$$\mu_{\tilde{A}_o}(a_i) = \max_k \mu_{\tilde{U}_{io}}(u_k)$$

6. To determine the best $a_o$ option. Obviously, the best solution is the one with the highest value of belonging to the set $\tilde{A}_o$:

$$\mu_{\tilde{A}_o}(a_o) = \max_i \mu_{\tilde{A}_o}(a_i)$$

3. Results section

The proposed method was applied for solving the task of agricultural mobile robot control for picking strawberry in the climatic conditions of Central Russia. Intelligent control system of agricultural mobile robot for picking strawberry, such as Agrobot SW6010, should choose one of the options of picking berries, depending on the conditions of picking. The size of the strawberries field is 800 acres.

Let there be three possible solutions:

- $a_1$ – to pick only large berries;
- $a_2$ – to pick large and medium-sized berries;
- $a_3$ – to pick berries of all sizes, including small ones.

The profit depends on: weather conditions; efficiency of berry picking, berries weight; robot performance.

Berries weight.

The cost of large berries is about 1.5 times more than medium-sized ones and 4 times more than small ones.

Weather conditions.

Bad - a prolonged rain is expected, and the berries will not be collected for several days.
Satisfactory - rain is expected, it will go from 0.5 to 1 day, then the weather will be dry and sunny.
Good - sunny, dry weather is expected for a long period of time.

The time allowed for picking berries is from 0 to 3 days.

As mentioned earlier, one Agrobot SW6010 can pick strawberries from 800 acres in good conditions in 3 days.

Small - prolonged rain or sunny, dry and hot weather is expected in 0.5 days.
Average – good weather is expected, the time for picking berries, taking into account the ripening rate, is 1.5-2 days.
Large – good weather is expected, the time for picking berries, taking into account the ripening rate, is 2-2.5 days.

Very Large - good weather is expected, the time for picking berries, taking into account the ripening rate, is 3 days.

The productivity of the mobile robot.

The productivity of the mobile robot depends on the location of the field, the variety of berries, its yield in this year, etc.

Low - one robot can pick strawberries from 800 acres in poor conditions in 5 days.
Medium - one robot can pick strawberries from 800 acres in average conditions in 4 days.
High - one robot can pick strawberries from 800 acres in good conditions in 3 days.

Descriptions of possible conditions of berry picking:

\( x_1 \) - bad weather is expected; the time for picking berries before rain is 0.5 days, the productivity of the mobile robot is low;
\( x_2 \) - bad weather is expected; the time for picking berries before rain is 0.5 days, the productivity of the mobile robot is average;
\( x_3 \) - bad weather is expected, the time for picking berries before rain is 0.5 days, the productivity of the mobile robot is high;
\( x_4 \) - satisfactory weather is expected, the time for picking berries is 1.5-2 days, the productivity of the mobile robot is low;
\( x_5 \) - satisfactory weather is expected, the time for picking berries is 1.5-2 days, the productivity of the mobile robot is average;
\( x_6 \) - satisfactory weather is expected, the time for picking berries is 1.5-2 days, the productivity of the mobile robot is high;
\( x_7 \) - sunny, dry and hot weather is expected, berry picking can be continued in the following days, but the ripening rate will be high, the weight of the berries may decrease, the time for berry picking is 2-2.5 days, the productivity of the mobile robot is average;
\( x_8 \) - good weather is expected, berry picking can continue in the following days, but the ripening rate will be high, the weight of the berries may decrease, the time for berry picking is 3 days, the productivity of the mobile robot is average;
\( x_9 \) - good weather is expected, berry picking can continue in the following days, but the ripening rate will be high, the weight of the berries may decrease, the time for berry picking is 3 days, the productivity of the mobile robot is high;
\( x_{10} \) - good weather is expected, berry picking can continue in the following days, but the ripening rate will be high, the weight of the berries may decrease, the time for picking berries is 3 days, the productivity of the mobile robot is high.

The utility matrix, in this example, is the profit matrix from picked berries, is given linguistically and has the form:

\[
U = \begin{bmatrix}
-a_1 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\
-a_2 & VL & L & A & A & H & H & VH & VH & VH & VH \\
-a_3 & VL & VL & L & A & A & H & H & VH & VH & VH \\
\end{bmatrix}
\]

where the profit is given by sets \( \mathcal{U}_{ij} = \bigcup_k \mu_{ij}(u_k)/u_k, u_k \in U_1 = \{u_{ij}\}, k \in J, i \in I = \{1, \ldots, m\}, j \in J = \{1, \ldots, n\} \), where \( m = 3, n = 10 \):

VERY LOW: \( VL = \{1.0/0.1; 0.4/0.2\} \);
LOW: \( L = \{0.4/0.1; 1.0/0.2; 0.5/0.3\} \);
AVERAGE: \( A = \{0.4/0.3; 0.7/0.4; 1.0/0.5; 0.7/0.6; 0.4/0.7\} \);
HIGH: \( H = \{0.5/0.7; 1.0/0.8; 0.5/0.9\} \);
VERY HIGH: \( VH = \{0.5/0.9; 1.0/1.0\} \).

It was determined that the conditions for picking berries are described as follows:
\( \bar{X} = \{0.4/x_3; 0.8/x_4; 1.0/x_5; 0.7/x_6; 0.3/x_7\}, \)

that is, \( k \) takes values from 3 to 7.

Linguistically, this state can be expressed as follows: the conditions for picking berries are approximately defined, most likely satisfactory weather is expected (rain is expected, it will go from 0.5 to 1 day, then most likely the weather will be dry and sunny, but not for very long, no more than 2 days). The time for picking berries is not more than 2 days. Productivity during the collection on the first day is average, on the second day – high.

It is necessary to find the best way to use the mobile robot for picking berries, providing the greatest profit from picking berries in these conditions.

Calculations were carried out in accordance with the previously proposed algorithm.

1. Fuzzy utilities (profit) for various solutions for all \( i = \bar{v}_m, k \in J \), that is, for \( k = 3, 4, 5, 6, 7 \) were found by formula (2) and (3):

\[
\bar{U}_i^1 = \{0.4/A; 0.8/A; 1.0/H; 0.7/H; 0.3/VH\} = \{(0.4 + 0.8 - 0.4 \cdot 0.8)/A; (1.0 + 0.7 - 1.0 \cdot 0.7)/H; 0.3/VH\} = \{0.88/A; 1.0/H; 0.3/VH\}; \\
\bar{U}_i^2 = \{0.4/L; 0.8/A; 1.0/A; 0.7/A; 0.3/HH\} = \{(0.4 + 0.8 + 0.8 \cdot 1.0)/A; 0.7/A; 0.3/H\} = \{0.4/L; 1.0/A; 0.3/H\}; \\
\bar{U}_i^3 = \{0.4/VL; 0.8/L; 1.0/L; 0.7/A; 0.3/A\} = \{0.4/VL; 0.8 + 0.8 \cdot 1.0)/L; 0.7 + 0.3 - 0.7 * 0.3)/A\} = \{0.4/VL; 1.0/L; 0.79/A\}; \\
\bar{U}_i^4 = \{0.4/L; 1.0/L; 0.79/A\} = \{0.4/L; 1.0/L; 0.79/A\}; \\
\bar{U}_i^5 = \{0.4/L; 1.0/L; 0.79/A\} = \{0.4/L; 1.0/L; 0.79/A\}.
\]

2. \( \bar{U}_i^1 \) on the exact utilities for all, \( i = \bar{v}_m, k \in J \) is, for \( k = 3, 4, 5, 6, 7 \) were calculated. To do this, values of the sets \( A \) and \( H \) (for \( i = 1 \)) instead sets \( A \) and \( H \) were substituted:

\[
\bar{U}_i^1 = \{(0.88/0.4/0.3; 0.7/0.4; 1.0/0.5; 0.7/0.6; 0.4/0.7); 1.0/0.5/0.7; 1.0/0.8; 0.5/0.9\}; \\
0.3/0.5/0.9; 1.0/1.0\} \}
\]

Simplification was done on the basis of formula (4):

\[
\bar{U}_i^2 = \{0.4/L; 1.0/A; 0.3/H\} = \{0.4/0.4/0.1; 1.0/0.2; 0.5/0.3; 1.0/0.4/0.3; 0.7/0.4; 1.0/0.5; 0.7/0.6; 0.4/0.7\}; \\
\bar{U}_i^3 = \{0.4/VL; 1.0/L; 0.79/A\} = \{0.4/L; 1.0/L; 0.79/A\}; \\
\bar{U}_i^4 = \{0.4/L; 1.0/L; 0.79/A\} = \{0.4/L; 1.0/L; 0.79/A\}; \\
\bar{U}_i^5 = \{0.4/L; 1.0/L; 0.79/A\} = \{0.4/L; 1.0/L; 0.79/A\}.
\]

3. The maximizing sets were determined by formula (5):

\[
Y = \{0.3/0.4/0.5/0.6; 0.7/0.8/0.9; 1.0\} \cup \{0.1/0.2/0.3/0.4/0.5; 0.6/0.7; 0.8/0.9; 1.0\}; \\
Y = \{0.3/0.4/0.5/0.6; 0.7/0.8/0.9; 1.0\} \cup \{0.1/0.2/0.3/0.4/0.5; 0.6/0.7; 0.8/0.9; 1.0\}; \\
Y = \{0.3/0.4/0.5/0.6; 0.7/0.8/0.9; 1.0\} \cup \{0.1/0.2/0.3/0.4/0.5; 0.6/0.7; 0.8/0.9; 1.0\};
\]

Hence, \( \sum_{max} = sup Y = 1.0 \), the corresponding maximizing sets have the form:

\[
\bar{U}_{1m} = \{0.3/0.3/0.4/0.4; 0.5/0.5; 0.6/0.6; 0.7/0.7; 0.8/0.8; 0.9/0.9; 1.0/1.0\}; \\
\bar{U}_{2m} = \{0.1/0.1; 0.2/0.2; 0.3/0.3; 0.4/0.4; 0.5/0.5; 0.6/0.6; 0.7/0.7; 0.8/0.8; 0.9/0.9\}; \\
\bar{U}_{3m} = \{0.1/0.1; 0.2/0.2; 0.3/0.3; 0.4/0.4; 0.5/0.5; 0.6/0.6; 0.7/0.7\};
\]
4. The optimizing sets $\widetilde{U}_{10}$ were determined by formula (6):

$$\widetilde{U}_{10} = \{\min(0.4; 0.3)/0.3; \min(0.7; 0.4)/0.4; \min(0.88; 0.5)/0.5; \min(0.7; 0.6)/0.6; \min(0.7; 0.7)/0.7; \min(1.0; 0.8)/0.8; \min(0.65; 0.9)/0.9; \min(0.3; 1.0)/1.0\} = \{0.3/0.3; 0.4/0.4; 0.5/0.5; 0.6/0.6; 0.7/0.7; 0.8/0.8; 0.65/0.9; 0.3/1.0\}$$

$$\widetilde{U}_{20} = \{\min(0.4; 0.1)/0.1; \min(0.4; 0.2)/0.2; \min(0.64; 0.3)/0.3; \min(0.7; 0.4)/0.4; \min(1.0; 0.5)/0.5; \min(0.7; 0.6)/0.6; \min(0.58; 0.7)/0.7; \min(0.3; 0.8)/0.8; \min(0.3; 0.9)/0.9\} = \{0.1/0.1; 0.2/0.2; 0.3/0.3; 0.4/0.4; 0.5/0.5; 0.6/0.6; 0.7/0.7\}$$

$$\widetilde{U}_{30} = \{\min(0.64; 0.1)/0.1; \min(1.0; 0.2)/0.2; \min(0.7; 0.3)/0.3; \min(0.7; 0.4)/0.4; \min(0.79; 0.5)/0.5; \min(0.7; 0.6)/0.6; \min(0.4; 0.7)/0.7\} = \{0.1/0.1; 0.2/0.2; 0.3/0.3; 0.4/0.4; 0.5/0.5; 0.6/0.6; 0.7/0.7\}$$

5. The set that represents the optimal solution was found by the formula (7):

$$\mu_4(\tilde{A}_1) = \max(0.3; 0.4; 0.5; 0.6; 0.7; 0.8; 0.65; 0.3) = 0.8$$

$$\mu_5(\tilde{A}_2) = \max(0.1; 0.2; 0.3; 0.4; 0.5; 0.6; 0.58; 0.3; 0.3) = 0.6$$

$$\mu_6(\tilde{A}_3) = \max(0.1; 0.2; 0.3; 0.4; 0.5; 0.6; 0.4) = 0.6$$

Thus $\tilde{A}_0 = \{0.8/\tilde{a}_1; 0.6/\tilde{a}_2; 0.6/\tilde{a}_3\}$.

6. The best option $\tilde{a}_i$ was found based on the formula (8).

Thus, the best option is $\tilde{a}_i$. The intelligent mobile robot control system, in the specified situation and under the given state of the harvest conditions, will select $\tilde{a}_i$ - to collect only large berries.

4. Discussion section and conclusions

Since berry harvesting depends on the weather conditions and the duration of good weather, the timing and speed of berry ripening and on the efficiency of picking berries, the conditions of the harvesting are not known accurately and, in addition, the usefulness of solutions for berry harvesting in different environmental conditions is not accurately determined. In this case, the choice of a solution will take place with qualitative uncertainty. Thus, the situations that arise will be ambiguous and unclear.

It is proposed to use artificial intelligence technologies to solve this problem. The procedure for decision-making by an intelligent control system of the mobile robot under the qualitative uncertainty of berry picking conditions was developed. This procedure based on the selecting of options based on a fuzzy description of the state of the system and the outcomes.

The proposed method was used to solve the task of agricultural mobile robot control for picking strawberry in the climatic conditions of Central Russia. This method can be implemented in the development of software not only in the management of intelligent mobile robots picking berries, but also robots for other purposes.

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