ALGORITHM FOR OPTIMIZING THE MOVEMENT OF A MOUNTED MACHINE-TRACTOR UNIT IN THE HEADLAND OF AN IRREGULARLY SHAPED FIELD
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АЛГОРИТЪМ ЗА ОПТИМИЗИРАНЕ ДВИЖЕНИЕТО НА НАВЕСЕН МАШИННО-ТРАКТОРЕН АГРЕГАТ В ИВИЦАТА ЗА ЗАВИВАНЕ НА ПОЛЕ С НЕПРАВИЛНА ФОРМА

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ABSTRACT
Increasing the productivity of machine tractor units when cultivating the field is achieved by reducing the work time, which usually relates to seeking the shortest path of the unit in the field. Reducing the length of headland turns, which account for the largest proportion of the unit non-working moves, will result in higher productivity as well as less soil compaction in the headland. The article presents an algorithm for selection of a turn in the headland of a field of irregular shape. Existing theoretical correlations have been used to determine the length of the non-working move and the headland width when making T-turns. The selection of a turn is made on the basis of the minimum length of the non-working move, after which the width of the needed headland for the selected turn is calculated. This algorithm can be added to the on-board computer of the unit thus providing a more efficient way of moving, automatically generating a headland and following the trajectory of the selected turn by the unit.

РЕЗЮМЕ
Повишаването на производителността на машинно-тракторните агрегати при обработка на полето се извършва чрез намаляване на времето за работа, което обикновено се свежда до търсене на най-краткия път на агрегата в полето. Намаляването на дължината на завоите в края на полето, които са с най-голям дял от неработните ходове на агрегата, ще доведе до по-висока производителност, както и по-малко уплътняване на почвата в ивицата за завиване. В статията е представен алгоритъм за избор на завой в ивицата за завиване на поле с неправилна форма. Използвани са съществуващи теоретични зависимости за определяне на дължината на неработния ход и на широчината на ивицата за завиване при извършване на гъбовидни завои. Изборът на завой се прави на база минимална дължина на неработния ход, след което за избрания завой се определя широчината на необходимата за извършването му ивица за завиване. Този алгоритъм може да бъде добавен в бордовия компютър на агрегата и да осигури по-ефективен начин на движение, автоматично генериране на ивица за завиване и следване на траекторията на избрания завой от агрегата.

INTRODUCTION
The application of information technologies in agriculture allows to achieve complete automation of the operations performed by the agricultural machinery depending on the working conditions, as well as automatic guidance of the machine tractor units along certain trajectories in the field. These technologies enable the development of fully autonomous units that will be the basis for remote controlled agricultural production in the future (*Freyberger and Jahns, 2000*). Autonomous units must be able to make decisions about the way of their movement in the field depending on the specific conditions so as to achieve high efficiency of the operations performed.

To increase the efficiency of performing the mechanized operations, it is necessary to minimize the processing time, which is usually done by seeking the shortest path travelled by the machine tractor unit in the field. *Kroulik et al.* present an algorithm to search for the shortest path of movement in the field by choosing among 180 directions with a step of 1 degree. According to this algorithm, the shortest path is found, but the final decision is made by the farmer depending on the characteristics of the field. The optimization of the trajectory of the machine tractor unit results in reduction in the total length of the travelled path, where the greatest change is in the length of the non-working moves (*Kroulik et al., 2018*). When optimizing the direction of movement in a field of irregular shape not only the size and shape of the field have to be taken into consideration, but also slope, soil conditions, point of entry into the field, and other constraints. The direction in which the ratio between working and non-working moves is the greatest is considered to be the optimum one (*Chyba et al., 2013*).

An increase in efficiency is usually achieved by reducing the number and length of non-working moves. They mainly include the turns made at the end of the field and the moves to load the units. Jin and Tang propose an algorithm to search for the minimum number of turns in the field by determining the direction of movement. With a shuttle mode of movement, the algorithm reduces the number of turns by 16% and the time for making them by 25% (*Jin and Tang, 2010*). Other authors propose an algorithm that can be used to determine the headland points in fields of different shape. The principle is to measure the angle between each field border and the direction of movement. If the angle is greater than 10 degrees, that edge of the field is assumed to have a headland (*Aurbacher and Dabbert, 2009*). According to other authors, the headland is not needed when the angle is below 15 degrees (*Oksanen, 2018*).

The optimization of non-working moves is reduced to minimizing their length in the automatic generation of the moves (*Sabelhaus et al., 2013*). Algorithms used for minimization of the turns must be able to automatically determine the way of turning in the headland and the parameters of the turn depending on the data received from the navigation system about the position of the unit, the headland and the type of unit (*Freyberger and Jahns, 2000; Oksanen, 2018*).

There are different methods for determining the way travelled when making a turn, but the most commonly used is a geometric method, where the turn is represented using straight sections and curved sections of constant radius (*Backman et al., 2015*). In the computational methods, the trajectory of movement is presented as equations of spirals, clothoids, etc. in combination with simple shapes, but the complex calculations to create the required shape of the turn make these methods more difficult to apply (*Khan et al., 2017*). Backman et al. present an algorithm for generating a trajectory in the headland using arcs of variable curvature to transition between arcs of constant radius and/or straight lines. This algorithm is suitable for real-time use, as an average computation time of 0.36 s per turn has been achieved (*Backman et al., 2015*).

Hameed et al. used a method for geometric presentation of the field, which provides a map on which operative planning of the mechanized operations can be put in place. This method is supplied with methods for optimization of the unit's mode of movement. The little time required for calculation makes it possible to use the method in real time for fully automated agricultural units (*Hameed et al., 2010*). Usually, existing algorithms for optimization do not include changing the width of the headland for different direction of movement. *Yatskul et al.* proposed an algorithm for determining the width of the headland that allows adding trajectories to replicate the drivers' behaviour. This allows for a 7.5% reduction of the headland width compared to the actual field measurement and a 5.1% reduction of the largest width of the pear-shaped turn (*Yatskul et al., 2014*).

The headland width as well as the time to make the turn should be minimal. Tu uses a method to calculate the minimum required headland width depending on the angle it makes with the perpendicular to the direction of movement of the unit. The required headland width at the minimum time to make a turn is thus determined (*Tu, 2013*).

Automatic turning will allow the operator to focus more on performing the relevant technological operation (*Freyberger and Jahns, 2000*). Existing navigation systems for automatic turning make it possible for the machine tractor unit to follow different optimal movement patterns. Various algorithms can be added to modern navigation systems to optimize the mode of movement and plan the route of the units (*Bochtis and Vougioukas, 2008*). Such a system for movement in the headland can be successfully coupled with a device performing repetitive actions on the machine tractor unit (e.g. towbar control, PTO, hydraulic valves), allowing for full automation of operations (*Cariou et al., 2010 a, b*).

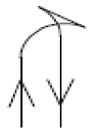
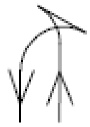
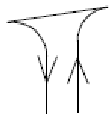
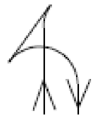
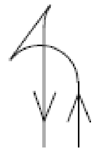
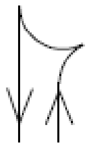
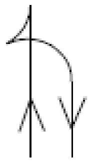
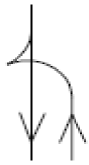
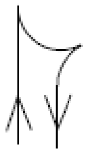
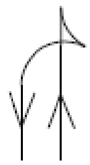
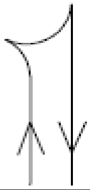
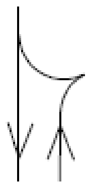
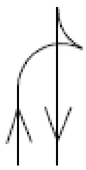
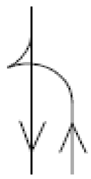
The objective of the present paper is to propose an algorithm for selecting a trajectory for movement when making a T-turn in a field of irregular shape and determine the headland width, to be applied in automatic control systems of agricultural units.

MATERIALS AND METHODS

The algorithm for selection of a turn has been developed for five types of T-turns made by machine tractor units. Each turn is in two variants - open and closed and is performed in two directions - from left to right and from right to left. A total of 20 turns have been described as shown in Table 1. The turns have been created by a geometric method using lines and arcs of circles of equal radius.

Table 1

Types of T-turns

Name of the turn	Type and direction of execution			
	Open turns		Closed turns	
	left to right	right to left	left to right	right to left
T-turns with straight-line backward move parallel to the field border				
T-turns with straight-line backward move not parallel to the field border				
T-turns with arc-shaped backward move				
T-turns with straight-line move upon entering the headland				
T-turns with straight-line move upon exiting the headland				

To develop the algorithm, the analytical correlations for determining the length of T-turns and the headland width have been used as described in (*Trendafilov and Tihanov, 2022 a, b*). A geometric method was used in the modeling of the turns, where the turn is represented by straight sections and curved sections of constant radius.

Input parameters are: the angle between the direction of movement and the field border (α); working width of the machine tractor unit (B); the kinematic length of the machine tractor unit (l_a); the turn radius of the machine tractor unit (R); the tractor wheel track (M); the longitudinal base of the tractor (H).

Figure 1 presents a diagram of one of the T-turns. The other designations on the figure are: the headland width (E); the beginning of the turn (point A); the end of the turn (point B); the centre of the corresponding curvilinear movement within the turn (point O_1 and point O_2); the rectilinear idle move length (l_g) when entering the headland.

The output parameters of the algorithm are: type of turn, length of the non-working move (l_n), headland width. The length of the non-working move in the headland is the sum of the length of the turn (l_T - the distance between point A and point B) and the length of the rectilinear non-working move l_g before or after making the turn. The criterion for the selection of a turn is the minimum length of the non-working move. For the selected turn, the actual headland width (E) and the number (k) of the unit moves required to handle it, which is a multiple of the working width of the machine tractor unit, have to be calculated.

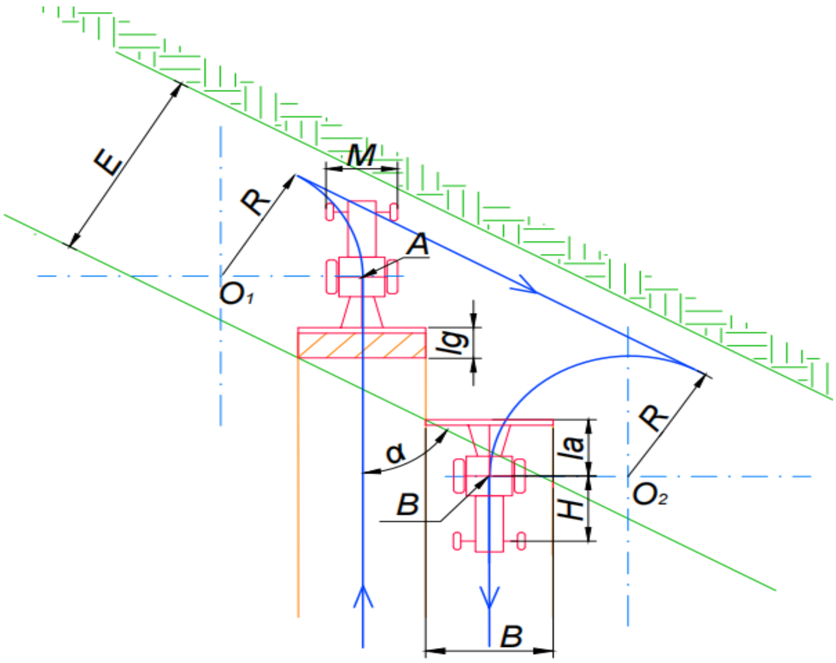


Fig. 1 – Diagram of an open T-turn

RESULTS

Figure 2 presents the block diagram of the algorithm, comprising the following steps:

1. Setting the input parameters: α, B, l_a, R, M and H.

2. Determining the idle move length when the machine tractor unit makes turns on a field of irregular shape and saving the obtained lengths in a database l_n with 20 elements and indices from 0 to 19 according to the set formulas (Fig. 3 - subalgorithm No. 1).

3. Finding the index of the first minimal element of the database l_n.

4. Calculating the whole part when dividing the index by 5. The resulting values determine the variant and direction of the turn (0 - open from left to right, 1 – open from right to left, 2 – closed from left to right, 3 – closed from right to left).

5. Calculating the remainder when dividing the index by an integer of 5. The resulting values determine the type of T-turn (0 – T-turn with a rectilinear reverse move parallel to the field border, 1 – T-turn with a rectilinear reverse move not parallel to the field border, 2 – T-turn with an arched reverse move, 3 – T-turn with a rectilinear move upon entering the headland, 4 – T-turn with a rectilinear move upon leaving the headland).

6. Visualization of the type of T-turn that corresponds to the index of the first minimal element (Fig. 4 - subalgorithm No. 2).

7. Determining the number of moves of the unit and the headland width (Fig. 5 - subalgorithm No. 3).

The block diagram for subalgorithm No. 1 (Fig. 3) presents the calculation of the length of the non-working move in an open T-turn with a rectilinear reverse move parallel to the field border when moving from left to right. The lengths of the other turns are calculated according to the analytical correlations described in (*Trendafilov and Tihanov, 2022 b*).

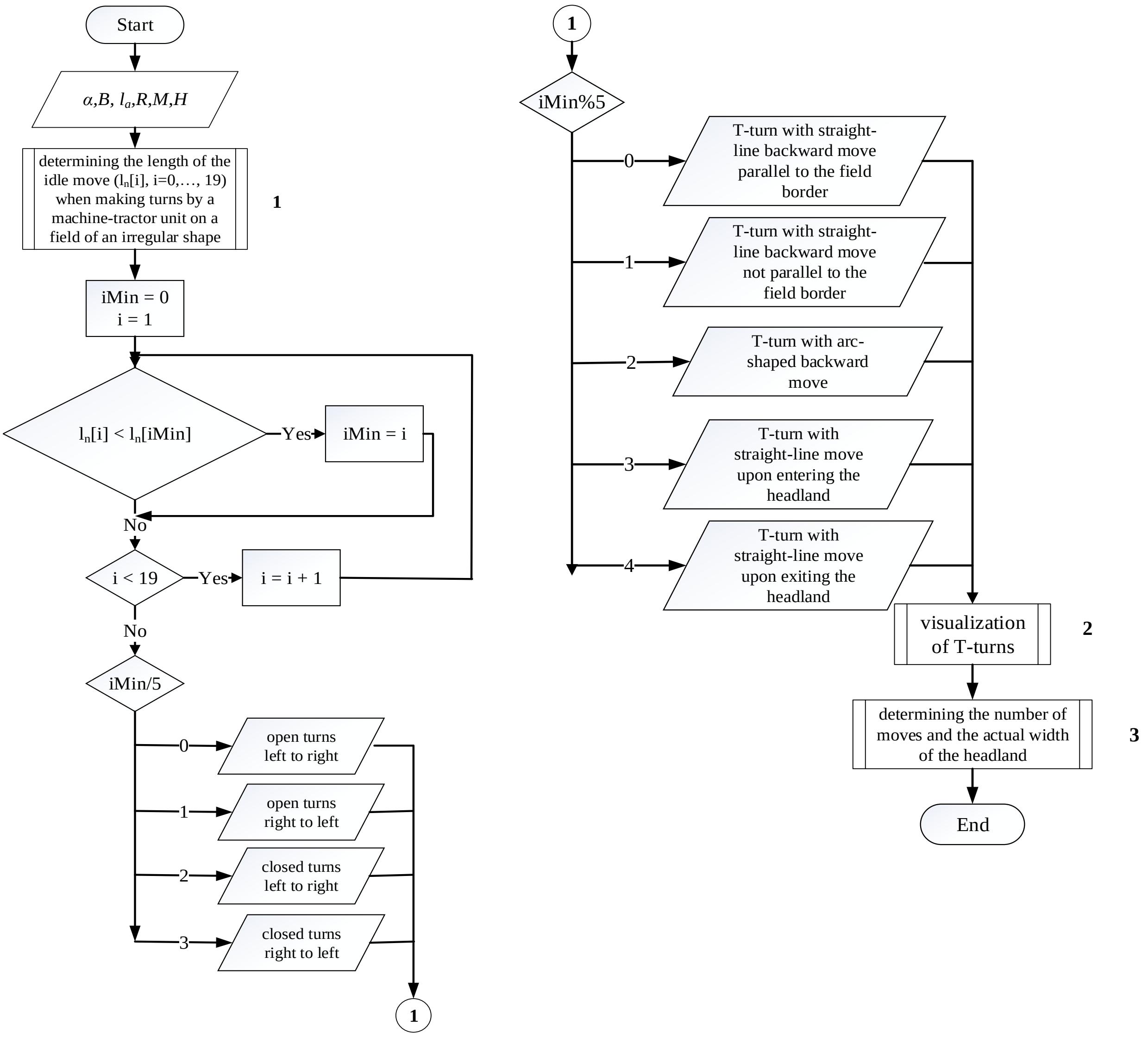


Fig. 2 – Block diagram of an algorithm for selection of a turn

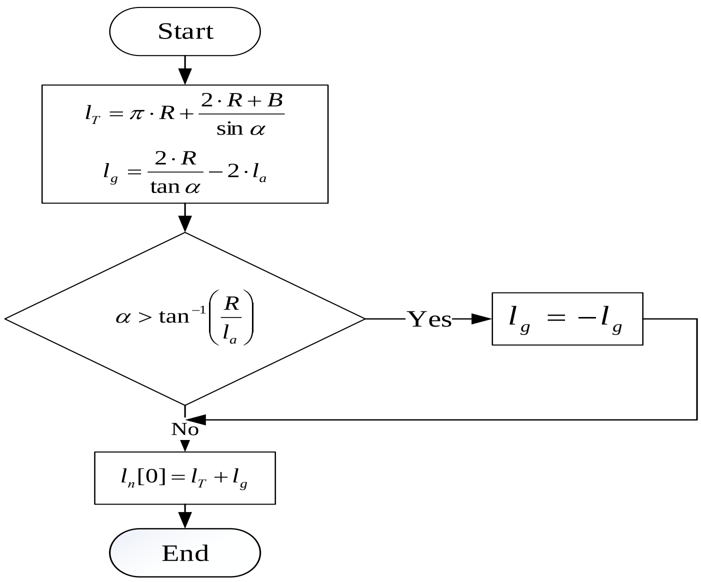


Fig. 3 – Block diagram of subalgorithm No. 1 for calculating the length of the non-working move when making a turn

The block diagram for subalgorithm No. 2 (Fig. 4) visualizes the selected turn of minimum length, and according to its number, the corresponding graphic image from Table 1 is presented.

The block diagram for subalgorithm No. 3 (Fig. 5) defines the number of moves k and the headland width for an open T-turn with a rectilinear reverse move parallel to the field border when traveling from left to right. The widths of the other turns are calculated according to the analytical correlations described in (*Trendafilov and Tihanov, 2022 a*). The number of moves has to be the smallest integer greater than or equal to the quotient of the theoretical headland width (E) and the working width of the machine tractor unit (B). The actual headland width is calculated as the product of the specified number of moves and the working width of the machine tractor unit.

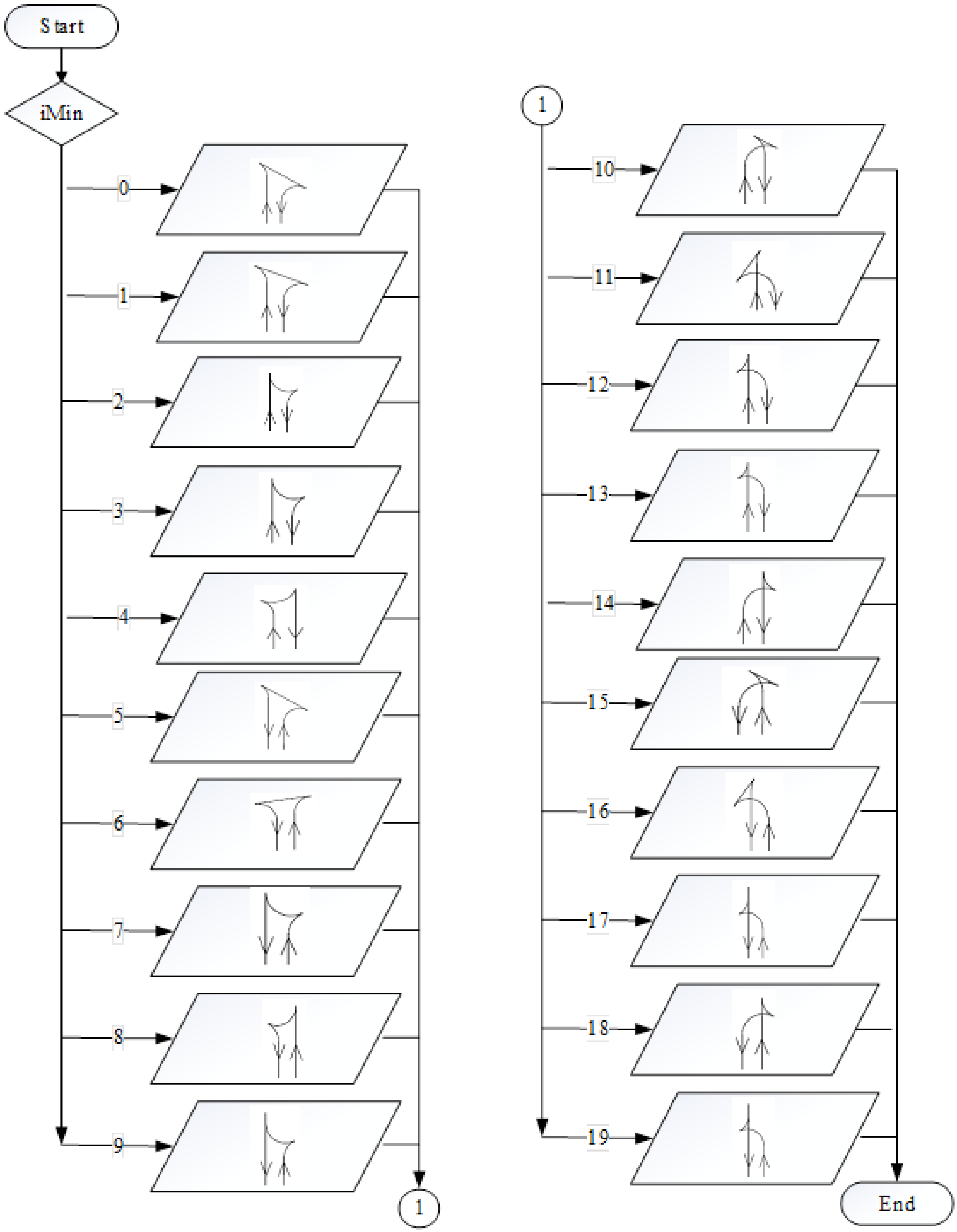


Fig. 4 – Block diagram of subalgorithm No. 2 for visualization of the selected turn

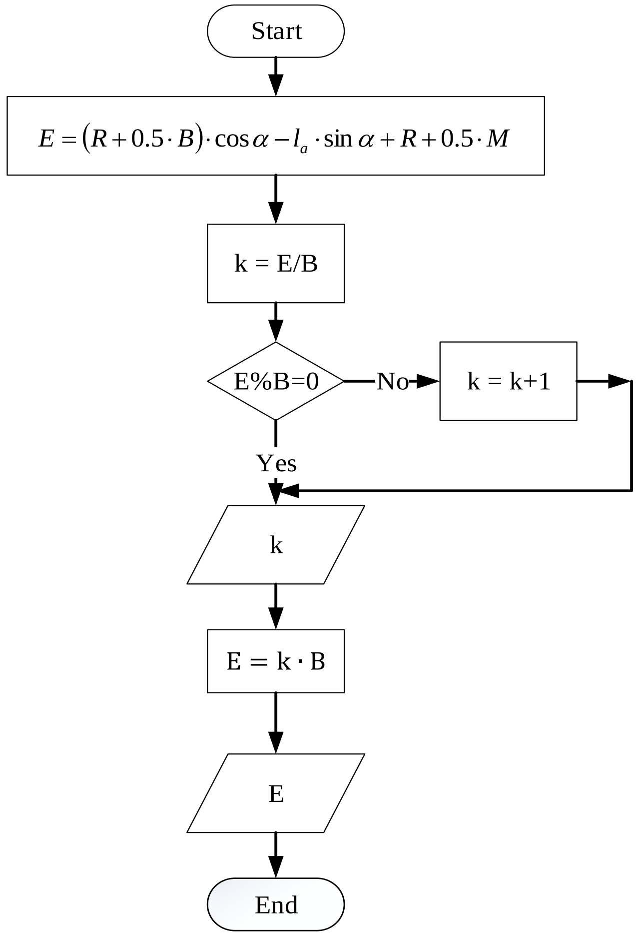


Fig. 5 – Block diagram of subalgorithm No. 3 for headland width and number of moves in it

CONCLUSIONS

An algorithm has been developed for selection of a turn in the headland of a field of irregular shape based on existing theoretical correlations for determining the length of 5 types of turns with a total of 20 variants of their execution. The selection of a is made on the basis of the minimum length of the non-working move, after which the headland width necessary for its execution is determined for the selected turn. The algorithm includes multiple subalgorithms, and in this case only subalgorithms for determining the non-working move and the headland width in one of the 20 types of turns have been demonstrated. This algorithm can be added to the on-board computer of the machine tractor unit and based on the characteristics of the unit and the angle between the direction of movement and the field border to determine the turn with the smallest length of the non-working move, visualize it on the screen and determine the width of the needed headland. This will allow the operator to use the most efficient way of movement, and when combined with the navigation system, the trajectory of the unit in the headland could be generated and followed. For this purpose, it is necessary to develop a computer program based on the presented algorithm, which is the subject of future work.

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REFERENCES

[1] Aurbacher J., Dabbert S. (2009). Integrating GIS-based field data and farm modeling in a watershed to assess the cost of erosion control measures: An example from southwest Germany, *Journal of soil and water conservation*, *64* (5), 350-362;

[2] Backman J., Piirainen P., Oksanen T. (2015). Smooth turning path generation for agricultural vehicles in headlands. *Biosystems engineering*, 139, 76-86;

[3] Bochtis DD., Vougioukas SG. (2008). Minimising the non-working distance travelled by machines operating in a headland field pattern, *Biosystems engineering*, 101, 1-12;
[4] Cariou C., Lenain R., Thuilot B., Humbert T., Berducat M. (2010a). Maneuvers automation for agricultural vehicle in headland. *AgEng 2010 Conference, 2010*, September 6-8, Clermont-Ferrand, France;
[5] Cariou C., Lenain R., Berducat M., Thuilot B (2010 b). Autonomous maneuvers of a farm vehicle with a trailed implement in headland, ICINCO 2010, *Proceedings of the 7th International Conference on Informatics in Control, Automation and Robotics*, Volume 2, Funchal, Madeira, Portugal, June 15-18, 109-114;
[6] Chyba J., Kroulik M., Vitek P., Kumhala F. (2013). Proposals for field work rides and their optimization according to shape of land, *12th International Scientific Conference Engineering for Rural Development*, Jelgava, Latvia, 111-114;
[7] Freyberger F., Jahns G. (2000). Symbolic course description for semiautonomous agricultural vehicles, *Computers and Electronics in Agriculture*, 25, 121-132;
[8] Hameed IA., Bochtis DD., Sørensen CG., Nøremark M. (2010). Automated generation of guidance lines for operational field planning, *Biosystems engineering*, 107, 294-306;
[9] Jin J., Tang K. (2010). Optimal coverage path planning for arable farming on 2D Surfaces, *Transactions of the ASABE*, *53* (1), 283-295;
[10] Khan A, Noreen I., Habib Z. (2017). On complete coverage path planning algorithms for non-holonomic mobile robots: survey and challenges, *Journal of Information Science and Engineering*, *33*(1), 101-121;
[11] Kroulik M., Hula J., Brant V. (2018). Field trajectories proposals as a tool for increasing work efficiency and sustainable land management, *Agronomy Research*, 16 (4), 1752-1761;
[12] Oksanen T. (2018). Path Planning Algorithms for Agricultural Machines, Helsinki University of Technology, *Automation Technology Laboratory, Series A: Research Reports* No 31, Espoo;
[13] Sabelhaus D., Röben F, M. zu Helligen LP, Lammers, PS. (2013). Using continuous-curvature paths to generate feasible headland turn manoeuvres. *Biosystems engineering*, 116, 399-409;
[14] Trendafilov K., Tihanov G. (2022 a). Comparative analysis of the headland width when making T-turns by a mounted machine-tractor unit on an irregularly-shaped field, *INMATEH - Agricultural Engineering*, *67* (2), 221-232, doi: https://doi.org/10.35633/inmateh-67-22
[15] Trendafilov K., Tihanov G. (2022 b). Comparative analysis of the idle move length when making T-turns by a mounted machine tractor unit in a field of irregular shape, *INMATEH - Agricultural Engineering*, *68* (3), 457-470, doi: https://doi.org/10.35633/inmateh-68-45
[16] Tu X. (2013). Robust navigation control and headland turning optimization of agricultural vehicles, *Graduate Theses and Dissertations*, Paper 13188;
[17] Yatskul A., Lemiere JP, Delion C. (2014). On an automated headland turn of wide width air seeders, RHEA, *Second International Conference on Robotics and associated High-technologies and Equipment for Agriculture and forestry*, 21-23 May 2014, Madrid, Spain, 239-246.