# SYNTHESIS OF MACHINE-TRACTOR UNIT AUTOMATIC CONTROL SYSTEM FOR INTER-ROW CULTIVATION OF SUGAR BEET

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**Abstract.** This paper presents a design for an automatic control system for a tractor-mounted unit used for inter-row cultivation of sugar beet. A block diagram of the single-loop automatic control system is provided. The automatic control system has been developed to automatically shift the agricultural machine (cultivator) laterally relative to the tractor frame along the rows of sugar beet. The control signal is provided by a furrow sensor mounted in front of the tractor. In the absence of a furrow, a light-sensitive sensor (camera) can be used. A Class 1.4 wheeled tractor with a USMK-5.4B cultivator was used to conduct field trials of the prototype automatic control system for the machine-tractor unit. The tractor hitch adjustment mechanism allows the cultivator to be moved laterally relative to the tractor frame. Experiments were conducted on inter-row cultivation of sugar beet crops for seven variants of cultivation technology, differing in the method of controlling the machine-tractor unit. For the machine-tractor unit comprising a Class 1.4 tractor and a USMK-5.4B cultivator, the automatic control system with a cultivator adjustment device provides distribution densities of the cultivator working body deviation of 1.22 $cm^2$ and 1.25 $cm^2$, respectively, a safety zone width of 6.6 cm at 1.56 $m \cdot s^{-1}$ and 6.8 cm at 2.17 $m \cdot s^{-1}$. Field experimental studies of the control accuracy of an agricultural machine (cultivator) using lateral machine displacement demonstrate a possible solution to the problem of ensuring a minimum safety zone (8-10 cm) during inter-row cultivation of row crops.

**Keywords:** automatic control system, machine-tractor unit, cultivator, corrective device, sugar beet, safety zone.

## Introduction

The development of an automatic control system for a tractor-mounted unit used for inter-row cultivation of sugar beet is a complex task aimed at improving precision, efficiency and productivity of agricultural operations, as well as reducing operating costs and enhancing the quality of soil cultivation [1; 2]. Such a system must ensure optimal interaction between the tractor and the working implement, adapting to changing field conditions and agronomic requirements [3; 4].

The key aspects of developing an automatic control system for inter-row cultivation of sugar beet are: optimisation of transmission parameters and engine operating modes; control of the direction of movement of the tractor and agricultural machinery (navigation); optimisation of implement design; monitoring, diagnostics and forecasting, as well as integration of machine-tractor unit systems with precision farming systems.

Automatic transmission gear selection is crucial for minimising fuel consumption and maximising traction efficiency [5]. The use of artificial neural networks can be effective for real-time prediction and optimisation of specific fuel consumption and fuel consumption per hectare, adapting to soil conditions [5]. For example, a study of various engine operating modes when a tractor is coupled with a rotary tiller demonstrated their impact on work productivity and fuel consumption [6].

For inter-row cultivation, high precision in the movement of the tractor-implement combination is critical to avoid damaging the plants. The automatic control system must integrate GPS/GNSS systems to maintain the set trajectory with minimal deviations [2; 7]. Based on GPS/GNSS data and soil sensors, the system can adapt the travel speed and working depth, taking into account the spatial heterogeneity of the field. This allows for improved productivity and work quality [2].

An automatic control system for inter-row cultivation of sugar beet must be integrated with broader precision farming systems (VRA, automatic steering, ISOBUS) to collect and analyse data on the field, soil, yield and other factors, enabling more informed decisions and optimising operations based on spatial variability in conditions [2].

At the same time, accurate guidance of the implement is often more critical than guidance of the tractor because the cultivator tools are the elements that can damage the crop. Reviews of automated weed control identify guidance, crop and weed detection, actuation and field mapping as core subsystems [14], and classical agricultural guidance studies describe GPS/GNSS, machine vision, inertial, geomagnetic and tactile sensors as possible sources of navigation information [15; 16].

For sugar beet and other row crops, vision-based row detection and autonomous navigation have been tested previously [17; 18], while a recent review emphasises that vision guidance remains challenged by unstructured field backgrounds, changing illumination, weed density and crop-growth stage [19]. This explains why the present study uses a mechanical furrow copier as the primary sensor and regards a camera sensor as an alternative when a furrow is absent.

Overall, the development of an automated control system for inter-row cultivation of sugar beet crops is a multi-factor process requiring the integration of cutting-edge technologies, such as artificial neural networks, GPS/GNSS, monitoring systems and digital twins, to achieve maximum efficiency and sustainability in agricultural production [2; 4; 5; 8-10]. However, scientifically sound principles for designing such control systems must be based on in-depth research into the behaviour of the machine-tractor units themselves, which these systems are capable of operating under real field conditions. The methodology for studying such units is set out in detail in [11-13]. Only through the integration of such approaches can further success be achieved in the creation of robotic systems for crop management.

## Materials and methods

A block diagram of the automatic control system for the lateral displacement of the cultivator relative to the tractor is shown in Fig. 1 and Fig. 2.

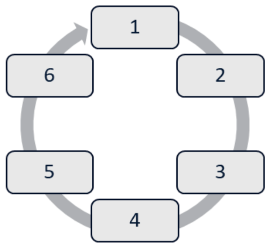


Fig. 1. **Block diagram of the automatic control system for a machine-tractor unit:** 1 – copying device; 2 – control unit; 3 – electric hydraulic distributor; 4 – hydraulic cylinder; 5 – hitch mechanism (correction device); 6 – cultivator

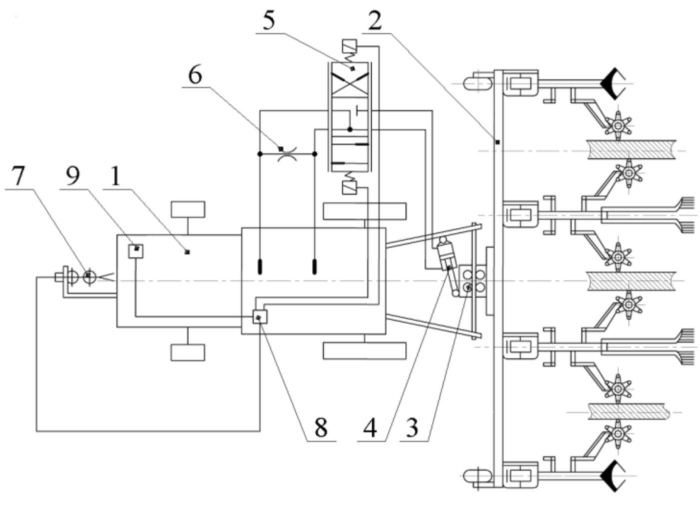


Fig. 2. **Diagram of a machine-tractor unit with an automatic control system and cultivator direction correction mechanism:** 1 – tractor; 2 – cultivator; 3 – correction device; 4 – hydraulic cylinder; 5 – electric hydraulic distributor; 6 – relief valve; 7 – copying device; 8 – control unit; 9 – battery (generator)

The principle of operation of this system was as follows. When the tractor-cultivator unit moves along the sugar beet rows, the system's tracking device 7 moves along the furrow in the rows, which is cut during sowing. If the working parts of the cultivator 2 deviate from the rows of sugar beet or the rows themselves are curved, the copying device 7, by rotating the rotor of the differential inductive sensor, generates an electrical signal proportional to the relative deviation of the machine-tractor unit from the direction of the crop rows. The electrical signal is transmitted via connecting cables to the electronic unit 8, where it is filtered and amplified.

Depending on the direction of deflection, the amplified signal is transmitted to one or the other solenoid of the three-position electric hydraulic valve 5, which directs the oil flow to the power hydraulic cylinder 4 of the controlled hitch (Fig. 3).


Fig. 3. **Controlled tractor hitch mechanism coupled with the USMK-5.4B cultivator**:
1 – cultivator frame; 2 – correction device; 3 – hydraulic cylinder; 4 – tractor hitch

Under the action of the hydraulic cylinder 4, the automatic corrector 3, together with the cultivator 2, moves in the direction of reducing the initial deviation from the sugar beet rows. The movement of the cultivator 2 continues until the copier 7 returns to the neutral position. In this case, the tines of the cultivator 2 will be set to the neutral position, i.e. the position for straight movement. The copying machine 7 is mounted on the frame of the cultivator 2 and is designed to generate a control signal proportional to the deviation of the cultivator working bodies from the sugar beet rows. The electronic unit 8 is mounted in the front of the tractor cab, to the left of the driver, and is designed to amplify the sensor signal, filter it, supply the sensor with alternating current, and control the solenoids of the three-position hydraulic valve. The front panel of the electronic unit 8 features a movement correction knob, designed to allow the driver to manually correct, during automatic driving, the average deviation of the cultivator from the rows caused by cross-slopes, uneven ground and variations in soil density. On the side of the device is a cover, under which the sensor gain adjustment switches are located. The electric hydraulic control valve 5 is mounted on a bracket at the rear of the tractor and connected to the tractor's hydraulic system. It is designed to control the oil flow to the hydraulic cylinder 4, as well as to control the movement of the tow hitch.

The use of the corrector allows agricultural implements (cultivators) to be moved in parallel with the tractor. The corrector is an integral part of the tractor, designed for inter-row cultivation of row crops with minimal buffer zones, and under operating conditions does not require additional costs for assembling the machine-tractor unit.

A Class 1.4 wheeled tractor with a USMK-5.4B cultivator was used to conduct field trials of the prototype automatic machine-tractor unit control system. The tractor hitch correction device allows the cultivator to be moved laterally relative to the tractor frame.

On the USMK-5.4B cultivator, a copying device is installed between the first and second sections on the left. The bracket is equipped with an IDU-1 inductive sensor, which is kinematically connected to the parallelogram hitch of the copying device. The electronic control unit of the automatic control system is installed in the cab of the tractor.

The movement of the machine-tractor unit, equipped with a prototype automatic steering system, was carried out along the furrows cut during sugar beet sowing, with the furrow widths of 2.5 m and 4.5 m. The quality of the automatic steering system is assessed based on the magnitude of the tracking error variance. To this end, the signal from the tracking device sensor was processed using a special programme from the measurement system for the dynamics and energetics of mobile machines [9; 11; 13].

An IP-179 fuel flow sensor was used to determine fuel consumption. The tractor-machine combination was driven in first high gear with a track length of 270 m along the furrow formed during sowing. Fuel consumption was measured for all cultivation technology variants, including sowing and three inter-row treatments.

In Table 1, $\Delta Q$ denotes the fuel consumed during the 270 m measured pass. For the 5.4 m working width of the USMK-5.4B cultivator, the equivalent area-specific fuel consumption can be calculated as $q_f = 10\Delta Q/(B \cdot L)$, L·ha$^{-1}$, where $B$ = 5.4 m and $L$ = 270 m. Table 1 also shows the combined optimization criterion

$$\frac{\Delta Q \sigma_{n-1}^2}{\upsilon};$$

which simultaneously penalizes high fuel consumption, high variance of deviations, and low operating speed.

The optimal tillage method was determined using the criteria of minimum fuel consumption ($\Delta Q$) and the average deviation of the cultivator working parts ($\sigma_{n-1}^2$) from the crop row, divided by the effective forward speed ($\upsilon$) of the tractor-machine combination.

## Results and discussion

We conducted field trials under real field conditions of elements of intensive vegetable crop cultivation technology using a machine-tractor unit equipped with an automatic control system. As a result of the research, the best option for vegetable crop cultivation technology was identified in terms of fuel consumption and operational quality (driving accuracy).

Experiments were carried out on inter-row cultivation of sugar beet for seven cultivation technology variants, differing in the method of controlling the machine-tractor unit.

- Variant 1. Cutting guide furrows during sowing. Crop maintenance using weeding robots and wide-cut flat cutters with weeding discs.
- Variant 2. Cutting guide furrows during sowing. Crop maintenance using standard working tools.
- Variant 3. Cutting guide furrows during sowing. Crop maintenance using rotary weeding machines.
- Variant 4. Cutting guide furrows during sowing. Crop maintenance using standard machinery.
- Variant 5. Conventional sowing (without cutting guide slots). Crop maintenance using weeding rotors and wide-cut flat cutters with copying discs.
- Variant 6. Conventional sowing (without cutting guide furrows). Crop maintenance using standard machinery.
- Variant 7. Cutting guide furrows during sowing. Crop maintenance using a cultivator with a correction mechanism and a machine-tractor unit equipped with an automatic control system.

The standard deviation ($\sigma_{n-1}^2$) within the measured area was determined by measuring, using a measuring tape, the distance between the row of plants and the cultivator working body at every metre.

The results of the experimental studies are presented in Table 1. Based on these results, probability density functions were plotted showing the deviation of the cultivator working body from the crop row (Fig. 4) for three inter-row tillage treatments.

The data in Table 1 show that process options No. 1 and No. 2 significantly increase fuel consumption by an average of 64%. To make the fuel-economy results explicit, the measured pass fuel use was converted to qf. The mean fuel consumption of variants No. 1 and No. 2 was 440.3 ml per pass (3.02 L·ha$^{-1}$), whereas variants No. 3-6 consumed 268.2 ml per pass (1.84 L·ha$^{-1}$) on average; therefore, variants No. 1 and No. 2 required about 64% more fuel than variants No. 3-6.

Table 1

**Data on measurements of the cultivator standard deviation by row and fuel consumption**

| Vari-ant No. | Speed $V$, m·s$^{-1}$ | $\sigma_{n-1}^2$, cm² | $\Delta = 3\sigma$, cm | Fuel use $\Delta Q$, ml | $\frac{\Delta Q \sigma_{n-1}^2}{\upsilon}$ |
|---|---|---|---|---|---|
| 1st inter-row cultivation | | | | | |
| 1 | 1.48 | 3.04 | 5.23 | 462.5 | 950.0 |
| 2 | 1.98 | 2.89 | 5.10 | 447.5 | 653.2 |
| 3 | 1.64 | 2.74 | 4.97 | 275.5 | 459.5 |
| 4 | 2.12 | 2.98 | 5.15 | 280.0 | 389.6 |
| 5 | 0.94 | 5.06 | 6.75 | 237.5 | 1278.5 |
| 6 | 1.11 | 5.75 | 7.19 | 252.5 | 1280.0 |
| 7 | 1.42 | 2.81 | 5.03 | 310.0 | 613.0 |
| 2nd inter-row cultivation | | | | | |
| 1 | 1.43 | 2.11 | 4.36 | 466.5 | 688.5 |
| 2 | 1.73 | 2.34 | 4.59 | 480.0 | 649.2 |
| 3 | 1.81 | 2.49 | 4.73 | 303.0 | 416.8 |
| 4 | 1.80 | 3.13 | 5.31 | 295.0 | 513.0 |
| 5 | 0.86 | 6.20 | 7.47 | 280.0 | 2018.6 |
| 6 | 0.99 | 7.45 | 8.19 | 280.0 | 2107.0 |
| 7 | – | 3.19 | 5.36 | – | – |
| 3rd inter-row cultivation | | | | | |
| 1 | 2.25 | 4.56 | 6.41 | 405 | 820.8 |
| 2 | 2.37 | 2.12 | 4.37 | 380 | 339.9 |
| 3 | 2.38 | 3.13 | 5.31 | 255 | 335.4 |
| 4 | 2.37 | 4.13 | 6.10 | 250 | 435.7 |
| 5 | 2.36 | 6.73 | 7.78 | 255 | 727.2 |
| 6 | 2.45 | 5.66 | 7.14 | 255 | 589.1 |
| 7 | 2.16 | 2.52 | 4.76 | 260 | 303.3 |

For the automated correction variant (No. 7), the available measurements for the first and third inter-row cultivations gave 285.0 ml per pass (1.95 L·ha$^{-1}$), which was about 35% lower than variants No. 1 and No. 2 but about 6% higher than variants No. 3-6; thus, the benefit of variant No. 7 is primarily improved row-following accuracy and reduced protective zone rather than absolute minimum fuel use.

For a machine-tractor unit comprising a Class 1.4 wheeled tractor and a USMK-5.4B cultivator, the automatic control system for the cultivator adjustment mechanism enables the following speeds: $V$ = 1.56 m·s$^{-1}$ and $V$ = 2.17 m·s$^{-1}$ distribution densities of the cultivator working body deviation of $\sigma_{n-1}^2$ = 1.22 cm$^2$ and $\sigma_{n-1}^2$ = 1.25 cm$^2$, respectively (Fig. 4).

Variants No. 5 and No. 6 (conventional sowing) are characterised by poor quality of inter-row cultivation between crop rows.

Variants No. 3 and No. 4 allow the protective zone to be maintained within 14 cm (±7 cm).

Variant No. 7 (cutting guide furrows during sowing. Crop maintenance using a cultivator with a correction mechanism and a machine-tractor unit equipped with an automatic control system) allows the protective zone to be maintained within 10 cm (± 7 cm).

When carrying out inter-row cultivation of sugar beet crops, a tractor-mounted unit comprising a Class 1.4 wheeled tractor and a USMK-5.4B cultivator, equipped with an automatic adjustment mechanism, leaves a protective zone 6.6 cm wide at a forward speed of 1.56 m·s$^{-1}$ and 6.8 cm at a speed of 2.17 m·s$^{-1}$. According to agrotechnical requirements, the protective zone must not exceed 10 cm.

Field experimental studies of the control accuracy of an agricultural machine (cultivator) using lateral machine displacement demonstrate a possible solution to the problem of ensuring a minimum safety zone (8-10 cm) during inter-row cultivation of row crops.

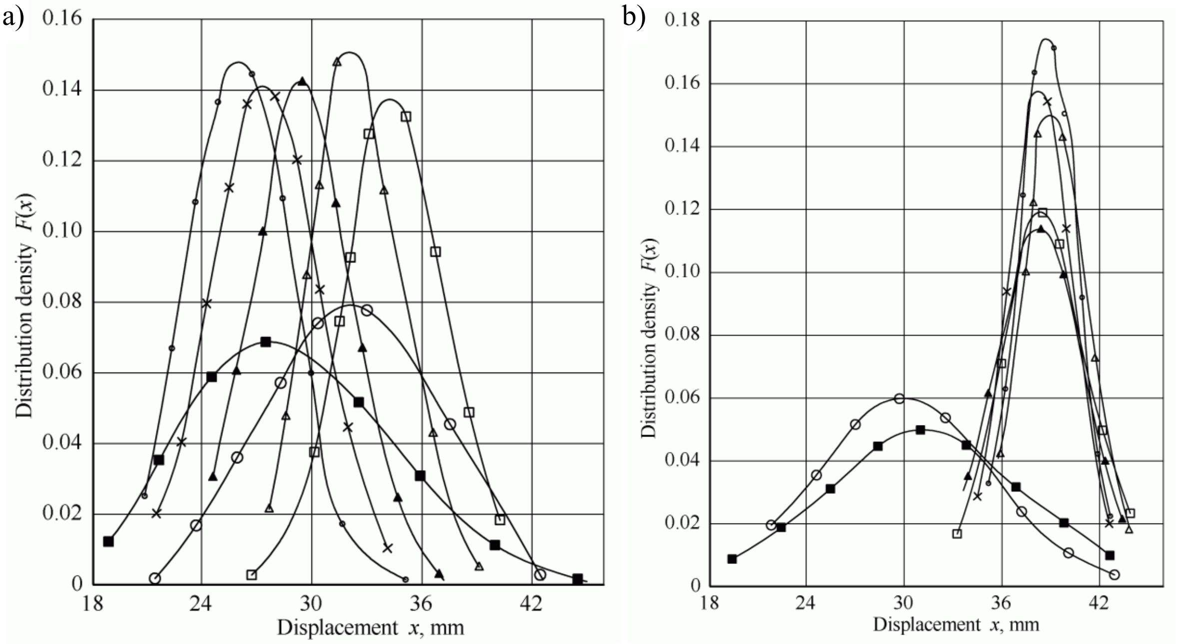


Fig. 4. **Distribution of deviation of the cultivator working body from the crop row**: a – first inter-row cultivation; b – second inter-row cultivation; • – treatment No. 1; × – treatment No. 2; Δ – treatment No. 3; □ – treatment No. 4; ○ – variant No. 5; ■ – variant No. 6; ▲ – variant No. 7

The obtained protective-zone width of 6.6-6.8 cm is in the range required for precision mechanical weeding and is consistent with the research trend toward active side-shift frames, camera- or GPS-guided hoes and combined cultivator–sprayer systems. Previous studies have shown that RTK-GPS or machine-vision guidance can provide high-accuracy implement positioning [20; 24; 25], while intelligent intra-row weeders reduce crop injury when plant position is detected reliably [21; 23]. Compared with such systems, the present furrow-copier and hydraulic side-shift solution is structurally simpler and less dependent on expensive navigation infrastructure, but future work should quantify its full-field fuel economy and test the alternative camera sensor under different light, weed-pressure and crop-growth conditions [19; 22].

## Conclusions

1 The use of an automatic correction device, controlled by an automatic control system, allows agricultural implements (cultivators) to be moved in parallel relative to the tractor, thereby enabling high-quality inter-row cultivation and reducing damage to plants in the crop rows.
2 For a machine-tractor combination comprising a Class 1.4 wheeled tractor and a USMK-5.4B cultivator, the automatic control system for the cultivator adjustment mechanism enables travel speeds of $V = 1.56$ m·s$^{-1}$ and $V = 2.17$ m·s$^{-1}$ with working body deviation distribution densities $\sigma_{n-1}^2 = 1.22$ cm$^2$ and $\sigma_{n-1}^2 = 1.25$ cm$^2$ respectively; a safety zone width of 6.6 cm at $V = 1.56$ m·s$^{-1}$ and 6.8 cm at $V = 2.17$ m·s$^{-1}$.
3 Field experiments investigating the control accuracy of an agricultural machine (cultivator) using lateral machine displacement demonstrate a possible solution to the problem of ensuring a minimum safety zone (8–10 cm) during inter-row cultivation of row crops.

## Author contributions

Conceptualisation, V.B., R.A.; methodology, A.A., Ye.I. and A.R.; software, R.A.; validation, I.H., Ye.I. and O.T.; formal analysis, V.B. and J.O.; investigation, V.A., V.K., Ye.I. and O.C.; data curation, A.A., V.B., Ye.I. and V.K.; writing – original draft preparation, V.B.; writing–review and editing, A.A.

and V.B.; visualisation, R.A., V.A.; project administration, V.B., Y.I.; funding acquisition, V.K. All authors have read and agreed to the published version of the manuscript.

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