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Original scientific paper

Efficiency of the autonomous modular system in the implementation of the spray application process in the vineyard

Sažetak

Autonomous modular system mounted on a conventional (CON) sprayer operating on the principle of pulse-width modulation (PWM) control of electromagnetic valves represents state-of-the-art technology for implementation controlled application of spray mixture without changing the operating parameters of the sprayer (e.g. spray pressure, nozzle size). In accordance with the principles of precision viticulture, the pulse-width modulation control is the primary technology, which allows the application of the required amount of spray mixture exclusively to the target areas of the vine without changing the droplet size spectrum and allows for even deposit quality and reducing the drift outside the target areas. In the vineyard, we tested an autonomous axial sprayer prototype throughout the entire spraying season in 2021 on which we have installed an autonomous modular system with enabled pulse-width control. We tested two modes of operation of the sprayer prototype, namely autonomous (continuous duty cycle control (DC: 0 to 100%)) and conventional (nozzle fully open at all time), at a steady spray speed of 6 kmh^{-1}. We compared the amount of PPP expressed as a percentage between autonomous and conventional mode of operation of the sprayer through individual nozzles on the sprayer. The maximum saving of the spray mixture of 69.8%, through an individual nozzle was measured at phenological stage of the vine BBCH 55. A comparative analysis between the CON and PWM mode of the spray mixture application showed that we saved 626.24 l per year in the automated mode of operation.

Key words: *algorithm, spray mixture, control, vine*

Introduction

Over the last two decades, great progress was made towards the development of autonomous alternative application techniques to implement optimization of the spray mixture application process in permanent orchards (Walkate & Cross, 2013) and vineyards (Siegfried et al., 2007; Llorens et al., 2011). To calculate the amount of spray mixture, there are many different types of technologies that work on the principle of different empirical and digital decision models (algorithms), the operation of which is based on the characteristic properties of the canopy. The effective application of the spray mixture application process depends on several factors, among which the characteristic feature of the canopy stands out (Llorens et al., 2011a; Solanelles et al., 2006) and the relationship between the amount of plant protection product (PPP) and the actual deposit of drops on canopy leaves, respectively (Gil et al., 2014). Gil et al. (2013) thus prepared that the cessation of risk in the application process of spray mixture application to the area without leaf area is associated with the consumption of doses of PPPs, which allows efficient operation of applications of the spray mixture application process throughout the canopy. Gil et al., (2007) and Vercruysse et al. (1999) prepared the correct direction and adjustment of spray mixture droplets on the leaf surface of the canopy leading to a significant

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increase in the efficiency of spray mixture application, which reduces the total consumption. doses of PPPs in line with the EU's strategic objectives (Llorens et al., 2010). All the listed reasons for reducing the consumption of PPP dose quantities have led to the development of new alternative spray mixture application techniques that can enable autonomous control of spray mixture dose quantities, which works on the principle of different decision models (algorithms), (Llorens et al., 2011a; Gil et al., 2013; Berk et al., 2016; Cheraiet et al., 2020).

The aim of the application technique for application of spray mixture drops on selected canopies of permanent crops should be the uniform application / deposit of spray mixture drops regardless of different developmental stages of vine crowning, which needs to be protected from various diseases and pests. Therefore, in the future, sustainable grape production will require increasing consideration of environmental aspects in the direction of reducing the consumption of spray mixture doses and their reliance on the surrounding area. We will be able to ensure this only with newly developed technologies that enable precise application of spray mixture drops, while taking into account the characteristic properties of the canopy, which will be measured with powerful advanced measuring technologies and which will control the flow of spray mixture through nozzles (Berk et al., 2016). The purpose of the research work presented by the authors refers to the digital 3D reconstruction of the left and right sides of the vine canopy, on different volumetric elements. A new measurement and control method (autonomous measurement and control of the quantities of spray mixture doses) was developed to optimize the spray mixture application process according to the leaf surface density.

Materials and methods

Vineyard

For experimental purposes, we used the vineyard of the Vinko Šerbinek farm, Slovenia (46°40'10.2 "N, 15°35'57.7" E, Figure 1a). The size of the vineyard area for the experiment was 2000 m^2. In the intensive vineyard, grafted vine seedlings based on Kober 5BB are planted, the seedlings contain a higher content of titratable acids, and the rootstock is used in individual wine-growing countries of Slovenia and was selected on the basis of professional criteria. The inter-row distance between seedlings is 230 cm and the maturing form is single-sparrow rearing (spar with up to ten eyes) with a plug (one to two eyes on the plug), with a vine stem height of 70 cm and an average distance between vines of 85 cm. In the experiment in the vineyard for digital evaluation of the density of the green wall of the leaf surface and the autonomous method of controlling the doses of broth, we included the grape variety "Sauvignon" (age 16 years). During the season of regular spraying in the vineyard, we tested two different modes of operation of the sprayer prototype, which we enabled to operate in conventional and autonomous mode for experimental purposes.

For experimental purposes, we used the vineyard of the agricultural farm Vinko Šerbinek located in Plač, northeaster Slovenia. The size of the experiment area was 2000 m^2, the GIS location of vineyard was 46°40'10.2" N, 15°35'57.7" E. Vines of cultivar 'Sauvignon' grafted on Kober 5BB rootstock are growing in an intensive 16-year old vineyard plantation with 2.3 m x 0.85 m spacing. The height of vine stocks steam was 0.7 m and plants were fixed in vertical trellis and trained according to standard unilateral Guyot with single-spawning (spar with up to ten buds) with a plug (one to two buds on the plug). In the experiment for the evaluation the LWA the vines were in BBCH91 phenological phase of growth (Lorenz et al., 1995).

Figure 1a: Design of an exeriment to optimize the process of spray mixture application in a vineyard
Slika 1a: Dizajn eksperimenta za optimizaciju procesa primjene škropiva u vinogradu

Figure 1b: Autonomous modular system for optimizing the spray mixture application process
Slika 1b: Autonomni modularni sustav za optimizaciju procesa nanošenja mješavine za prskanje

Figure 1c: Installation of DGPS measuring system close to the the vineyard
Slika 1c: Instalacija DGPS mjernog sustava u blizini vinograda

Modular measuring and control system

Modular electronic measuring and control system (installed on a conventional type of mounted tractor sprayer AGP 300 PRO, manufacturer Agromehanika, Kranj) for digital evaluation of leaf surface density and automated control of dose levels (individually by individual nozzles, Figure 1b) in the vineyard consists of three components. The first component consists of laser (LIDAR) measuring technology. With LIDAR measuring technology, which is mounted on a special support on a mounted sprayer, we digitally determine the amount of leaf surface density (different developmental stages of the vine) on an individual segment of the vine crown. In the experiment, we used a laser sensor model LMS111 manufactured by SICK. The SICK LMS111 laser rangefinder offers the IP67 protection standard, which means that it is also suitable for outdoor use in the vineyard. The Lidar LMS111 offers an excellent compromise between compact size and performance. It allows the capture of data with a frequency of 50 Hz and an angular resolution of 0.5 °. Its range is up to 20 m. Data transfer takes place in real time via Ethernet interface with a nominal speed of 100 Mbit / s.

The second component built into the modular system represents a microcontroller with an added Ethernet module, which takes care of the transfer of measurements from LIDAR measurement technology and autonomous control of mixture doses in pulse width mode via solenoid valves (hereinafter: EMV). 10 Hz EMV control duty cycle. We used a Teensy 3.6 microcontroller. The Teensy 3.6 microcontroller has a built-in 32-bit 180 MHz ARM Cortex-M4 processor, which offers enough processing power to process data from LIDAR measurement technology and control the amount of spray mixture through EMV in real time.

The third component is the DGPS measuring system (Figure 1c), which allows us to determine the driving speed and location of the modular measuring system to a few centimetres accurate. The location and velocity of the autonomous modular system were determined at a frequency of 10 Hz. We used the latest DGPS system from UBLOX, the F9P receiver model. The system enables two-frequency reception of GPS signal with RTK correction. The system consists of two parts. In the field near the vineyard, we install the DGPS reference station, which takes care of correcting the pseudo distances of the GPS receiver. Correction data is transmitted via a real-time data connection to a mobile station (mounted on a tractor), de-modulated and then used to correct GPS data.

Throughout the entire 2021 season, we carried out regular spraying via an autonomous sprayer prototype and simultaneously we evaluated digitally the size of the leaf surface density in real time via the digital number of points in the cloud, namely for the left and right halves of the canopy (picture). On the principle of autonomous recording of measurements via laser LIDAR measuring technology and an autonomous modular system, we thus enabled the digital evaluation of the density of the leaf surface of the vine. Information on the estimated value of leaf surface density was used in the decision model (soft logic algorithm), which later enabled the control of broth dose quantities in the range from 0% to 100% when optimizing the spray mixture application process. To analyse the doses of spray elderberry during the season of regular spraying, 8 individual species were selected in the permanent vineyard, namely in 4 individual species we performed the conventional mode of operation of the sprayer and the remaining 4 individual species autonomous mode of operation of the sprayer. In our case of experiments in the vineyard, we performed the conventional method of grape production where Table 1 shows the spray program used in the control of diseases (downy mildew and grapevine powdery mildew) in the vineyard.

The optimization of the process of conventional and autonomous operation of the sprayer prototype was performed in the vineyard owned by University of Maribor (Faculty of Agriculture and Life Sciences) and laboratories of University of Ljubljana (Faculty of Mechanical Engineering). On the principle of an autonomous modular system, which included digital measurements of leaf surface density, an autonomous module for controlling the amount of spray mixture and DGPS measuring system, we performed field optimization of the amount of dose of spray s mixture in conventional and autonomous mode. We compared the amount of spray mixture consumed expressed as a percentage between the autonomous and conventional mode of operation of the sprayer through the individual nozzles on the sprayer. During the season of regular spraying, we obtained data on the influence of autonomous mixture application on the occurrence of the disease (the degree of attack on leaves and grapes expressed as a percentage) and on the height and quality of yield in a vineyard with a classic cultivation form.

Three fungal diseases were assessed: powdery mildew (*Uncinula necator*), downy mildew (*Plasmopara viticola*), and grey mould (*Botrytis cinerea*). The disease rate was determined by direct visual scouting of the attacked % area of leaves or clusters. At each assessment 150 leaves or 150 clusters were randomly selected per each plot. The methodology followed EPPO standards (European Plant Protection Organisation) PP1/031(3) *''Plasmopara viticola"*, PP1/004(4) *"Uncinula necator"*, PP1/017(3) *"Botryotinia fuckeliana on grapevine"*, and the methodology described by Püntener (1981). The experiment was designed according to the system of randomized blocks with four replications. For the statistical analysis of the differences between the averages of treatments, we performed the ANOVA test and the Tukey HSD test ($\alpha<0.05$). We used the statistical program Statgraphics for Windows Centurion 15.1 (Statgraphics Technologies Inc., Virginia, USA).

Results

Table 1 shows the spraying program used for the control of diseases (downy mildew and grapevine powdery mildew) in the vineyard. In the 2021 season, we carried out 10 sprays in the vineyard for the location of the vineyard. Among the achieved key results are the testing of an autonomous modular system, which was installed on a mounted axial conventional sprayer type (AGP 300 PRO) and the testing was performed in real conditions in the vineyard. The autonomous modular system operated via advanced LIDAR laser measuring technology and a control system that enables continuous control of spray mixture dose rates according to an algorithm (decision model) according to leaf surface density by individual segments (volume elements) of the vine canopy. Through the DGPS navigation measuring system, we enabled the measurement of the speed of the carried autonomous prototype of the sprayer, which affected the consumption of dose quantities and the quality of application of spray mixture drops.

Table 1. Spraying program used in disease control in the vineyard during the regular spraying season, 2021.

Tablica 1. Program prskanja za suzbijanje bolesti u vinogradu tijekom redovne sezone prskanja, 2021.

Spraying program	Date of spraying
Quantities of PPP per 100 l of water: 1 kg manfedt, 2 kg cumulus DF, 2 l SY STAMAG SL	21 May 2021
Quantities of PPP per 100 l of water: 1 kg Qumulus DF, Ampexia 125 g, Caratan gold 1 dl, Microchelate zinc 0.25 kg	1 June.2021
Quantities of PPP per 50 l of water: Reeboot 0.15 kg, Spiroxd 0.2 l, Qumulus DF 0.75 kg	8 June 2021
Quantities of PPP per 50 l of water: Sfinga Extra 0.375 kg, Karatan Gold 350 EC 0.15 l, Qumulus DF 0.75 kg	16 June 2021
Quantities of PPP per 100 l of water: Sfinga Extra 0.375 kg, Karatan Gold 350 EC 0.15 l, Qumulus DF 0.75 kg	24 June 2021
Quantities of PPP per 100 l of water: Reeboot 80 g, Collis 80 ml, Qumulus DF 400 g, Mimic 120 ml	6 July 2021
Quantities of PPP per 100 l of water: Reeboot 80 g, Collis 80 ml, Qumulus DF 400 g, Mimic 120 ml	15 July 2021
Quantities of PPP per 100 l of water: Ampexia 100 g, Qumulus DF 400 g, Kosabi 300 SC 60 ml, Couparblau Z35WP 200 g	23 July.2021
Quantities of PPP per 100 l of water: Ampexia 100 g, Qumulus DF 400 g, Kosabi 300 SC 60 ml, Couparblau Z35WP 200 g	6 August 2021
Quantities of PPP per 100 l of water: Ampexia 120 g, Qumulus DF 500 g, Kosabi 300 SC 60 ml, Couparblau Z35WP 250 g	24 August 2021

After individual experiments in the vineyards, we performed two different methods of the spray mixture application process, with the amount of water at the planned spraying program for the experiments in the vineyard being 100 and 50 liters. In the experiment, we measured the current consumption of mixture doses for the left and right halves of the vine canopy using an electronic meter, for each individual species in the experiment, where we also measured the operating time of automated and conventional sprayer operation for each species. Table 2 shows the results of dose consumption on individual canopy segments with automated and conventional mode of operation of the sprayer prototype. In conventional operation, the sprayer nozzle was continuously opened throughout the optimization of the spray mixture application process. To optimize the mixture application process, we used different numbers of nozzles, calibrated according to the height of the green wall of the vine and at an angle to ensure even distribution of the jet with drops of spray mixture, which were evenly distributed on the green wall of the vine. We performed a thorough analysis of the effectiveness of both methods (conventional and automated) and also an analysis of the effectiveness of disease control for both methods. Table 2 shows a comparative analysis between the conventional and autonomous mode of operation of the sprayer prototype. Table 3 shows the analysis of disease control performance (downy mildew, grapevine powdery mildew and gray mold on grapes), for both modes of operation of the sprayer prototype.

Table 2. Comparative analysis between conventional and autonomous mode of operation of the sprayer prototype, year 2021.

Tablica 2. Usporedna analiza konvencionalnog i autonomnog načina rada prototipa prskalice, 2021. godina.

				Spray mixture saving [%]							
		Application time [s]		Nozzle (PWM)					Sum of savings	Amount PWM	Amount CON
Spraying	Date	PWM*	CON**	1	2	3	4	5	l/ha	l/ha	l/ha
1	21 May 2021	434.92	432.58	x	x	x	x	54.7	55.3	45.25	100.55
2	1 June.2021	443.72	458.5	x	x	x	69.8	43.5	113.83	87.28	201.11
3	8 June 2021	482.52	489.58	x	x	2.9	39.3	x	42.43	158.68	201.11
4	16 June 2021	575.02	499.34	x	x	50.0	13.3	14.4	78.04	223.62	301.66
5	24 June 2021	499.96	487.58	x	21.7	10.9	6.7	32.6	72.19	330.02	402.21
6	6 July 2021	479.44	487.32	8.2	8.2	6.3	5.0	28.6	56.61	454.36	502.77
7	15 July 2021	469.7	476.18	5.4	5.4	4.6	4.0	30.6	50.28	452.49	502.77
8	23 July.2021	436.38	449.16	5.6	5.6	5.1	4.1	27.9	48.41	454.36	502.77
9	6 August 2021	487.78	491.62	6.0	6.0	6.6	5.2	32.6	56.61	446.16	502.77
10	24 August 2021	449.32	461.74	8.1	8.1	7.9	5.8	22.3	52.54	450.23	502.77
Total									**626.24**	**3094.25**	**3720.49**

*PWM (pulse width modulation)

**CON (conventional)

1 (nozzle on top), 2 (nozzle in middle-top), 3 (nozzle in middle), 4 (nozzle in middle-bottom), 5 (nozzle in bottom)

Table 3 shows the results of the disease assessment, the sprayer experiment (conventional and automated mode of operation) the rate of attack on leaves and grapes expressed as a percentage (Sauvignon). For each measurement separately, we performed 600 assessments in the vineyard. According to the analysis, we found that there were no significant differences in disease control between the conventional and autonomous mode of operation of the nebulizer prototype.

Table 3. Estimates of disease, yield quantity and quality, experimental sprayer (conventional and automated mode of operation), year 2021

Tablica 3. Procjena bolesti, količine i kvalitete prinosa, pokusna prskalica (konvencionalni i automatizirani način rada), 2021.

Date	Mode of operation	Downy mildew cluster + flower (%)	Downy mildew Leaves (%)	Powdery mildew cluster (%)	Powdery mildew leaves (%)	Gray mold on cluster (%)
24 June 2021	Autonomous	0,17 A	0,22 A	0,0 A	0,0 A	
	Conventional	0,14 A	0,21 A	0,0 A	0,0 A	
26 July 2021	Autonomous	0,23 A	0,52 A	0,28 A	0,06 A	
	Conventional	0,21 A	0,41 A	0,14 A	0,04 A	
22 September 2021	Autonomous	0,26 A	3,25 A	1,45 A	8,24 A	8,24 A
	Conventional	0,33 A	3,60 A	2,01 A	2,87 A	3,63 A
				Yield (kg/ha)	**Sugar content (O°)**	**Total titratable acids (g/l)**
22 September 2021 (Harverst)	Autonomous			10434 A	96,25 A	6,54 B
	Conventional			11991 A	99,5 A	7,27 A

A….significant at p>0.05 (Tukey HSD test)

In the season (2021) of spraying, we used different numbers of nozzles on the left and right halves of the spraying set of the automated prototype sprayer. At the beginning of the growing season (developmental stage (BBCH 15) of the vine, Lorenz et al., 1994) we used two nozzles, one nozzle on the left and one on the left side of the automated sprayer and found a spray mixture saving of 55.3 l / ha compared to the conventional method of spraying. At the end of the growing season (developmental stage (BBCH 89) of the vine, Lorenz et al., 1994) we used ten nozzles, five nozzles on the left and right side of the automated sprayer, and found a saving of spray mixture of 52.54 l / ha compared to the conventional method of spraying. The greatest saving of spray mixture was found in the growing season (developmental stage (BBCH 55) of the vine, Lorenz et al., 1994), using four nozzles, two nozzles on the left and right side of the automated sprayer, and saving of spray mixture 113.83 l / ha compared to the conventional spraying method. The total saving of spray mixture during the entire growing season of wine in 2021 amounted to 626.24 l / ha, and in experimental experiments we used a mounted tractor sprayer AGP 300 PRO (nozzle type: Albuz ATR 80 °, flow: 1.07 l / min, working pressure: 10 bar). In the 2021 season, we evaluated the assessment of disease, quantities and quality of yield in selected vineyards in selected vineyards (the sprayer prototype operated in conventional and automated mode). We evaluated the disease assessment in June, July and September and found that there were no significant differences between the autonomous and conventional modes of operation. There was a small difference in the assessment of the disease (gray mold on grapes) in September, which can be attributed to the fact that there was more precipitation in September, which resulted in leaching of drops of spray mixture from leaves and grapes. Namely, in the autonomous mode of operation, fewer drops of spray mixture were generated than in the conventional mode of operation, optimization of the spray mixture application process, which resulted in less protection of grapes and grape leaves. In the analysis of the quantities and quality of grape yields, no significant differences were observed between the conventional and autonomous method of optimizing the spray mixture application process (Table 3).

Conclusions and discussion

Alternative techniques for optimizing the spray mixture application process work on the principle of electronic measuring systems for detecting the characteristic properties of vine canopies and represent one of the most important processes in meeting the conservation, economic and safety requirements of healthy grape production.

We found that the autonomous modular system significantly affects (especially in the earlier developmental stage of the vine) the application of the dose control process and directly affects the pulse width control of EMV, thus enabling more selective dosing of spray mixture on individual segments of the vine canopy.

Past research in the field of alternative spray mixture application techniques has shown that by detecting characteristic characteristics of the canopy based on various electronic measuring systems and using decision models to control mixture dose rates, we cannot always ensure precise target mixture application to the entire canopy leaf surface density structure. , due to the nozzles, which are fixed at the individual heights of the sprayer boom. Therefore, in the near future, more attention should be paid to an effective alternative mixture application technique, which will enable dynamic movement of the nozzles and deposition of mixture droplets at a constant distance from the vine canopy.

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Izvorni znanstveni rad

Učinkovitost autonomnog modularnog sustava za provedbu postupka prskanja u vinogradu

Sažetak

Autonomni modularni sustav postavljen na konvencionalnu (CON) prskalicu, koji operira na principu kontrole elektromagnetskih ventila modulacijom širine impulsa (PWM), predstavlja najsuvremeniju tehnologiju za provedbu kontrolirane primjene mješavine za prskanje bez promjene operativnih parametara prskalice (npr. pritisak prskanja, veličina mlaznice). U skladu s principima precizne vitikulture, kontrola modulacijom širine impulsa je primarna tehnologija, koja omogućava primjenu potrebne količine mješavine za prskanje isključivo na ciljana područja vinove loze, bez mijenjanja spektra veličine kapi, te omogućava ujednačenu kvalitetu nanosa i smanjenje zanošenja van ciljanih područja. U vinogradu je kroz cijelu sezonu prskanja u 2021. testiran prototip autonomne aksijalne prskalice, na koji je bio instaliran autonomni modularni sustav s omogućenom kontrolom širine impulsa. Testirana su dva načina rada prototipa prskalice, autonomni (kontinuirana kontrola radnog ciklusa (DC: 0 to 100%)) i konvencionalni (mlaznica potpuno otvorena sve vrijeme), pri standardnoj brzini prskanja od 6 kmh-1. Usporedili smo količinu sredstva za zaštitu bilja izraženu kao postotak između autonomnog i konvencionalnog načina rada prskalice kroz individualne mlaznice prskalice. Maksimalna ušteda mješavine za prskanje od 69,8%, kroz individualnu mlaznicu izmjerena je u fenološkoj fazi vinove loze BBCH 55. Komparativna analiza između CON i PWM načina primjene mješavine za prskanje pokazala je da je s automatiziranim načinom rada u godinu dana ušteđeno 626,24 L.

Ključne riječi: *algoritam, mješavina za prskanje, kontrola, vinova loza*