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Automation of a Prototype for Cutting, Sorting and Bundling of SRC Crops for Planting Purposes

Sorin Nanu[a] , Raul Ionel[b], Ciprian Dughir[b], Ioana Ionel[c]

[a]Department of Automation, The Faculty of Computers and Automation, University "Politehnica" Timişoara, Bd. Vasile Parvan, Nr. 2, 300223, Timişoara, Romania, Corresponding author: Tel.: +40726713893, Fax: 0040-256-403362, E-mail Address: sorin.nanu@upt.ro.

[b]Department of Measurements and Optical Electronics, The Faculty of Electronics and Telecommunications, University "Politehnica" Timişoara, Bd. Vasile Parvan, Nr. 2, 300223, Timişoara, Romania, Corresponding author: Tel.:+40723619912, Fax: 0040-256-403362, E-mail Address: raul.ionel@upt.ro.

[b]Department of Mechanical Machines and Transportation, The Faculty of Mechanics, University "Politehnica" Timişoara, Bd. Vasile Parvan, Nr. 2, 300223, Timişoara, Romania.

Abstract

This paper presents the design, implementation and testing of the automation component for a prototype machinery destined for cutting, sorting and bundling of harvested SRC crops for planting purposes. The device has been developed under the name Rod Picker and is the result of collaboration between six partners from four different countries. The Rod Picker project includes mechanical, automation, hydraulics and sensor measurement concepts. It operates according to conditions imposed by the beneficiaries - Short Rotation Coppice (SRC) farm owners, agricultural machinery and energy crops species producers. Freshly harvested material is cut (obeying diameter and length restrictions), sorted and bundled into packages ready for distribution. The process is automated, requiring little intervention on behalf of the operator. The cutting accuracy and speed of execution are two features which underline the efficiency of this device when compared against manual rod processing methods. Measurement errors of under ±2% are obtained between what the machine indicates and the manually calculated length. Functionality tests performed over several weeks, in both laboratory and industrial conditions, confirm that this system was properly designed and implemented. Regarding the economical evaluation the conclusion is that working with this machinery can decrease overall processing costs approximately five times when compared to manual labor.

Key words: Automated Processing; SRC Plantations; Energy Crops; Biomass; Prototype Cutting Machinery;

1. Introduction and related work

Biomass represents one of today's increasingly important renewable sources of energy. For this reason, biomass exploitation has proliferated in small combustion power plants, large coal fired plants (co-fired), steam turbine plants or small gasifiers. Scientists and engineers are focusing on projects which integrate the benefits of biomass resources into state of the art customized low-energy systems. Developing new prototypes and extensive testing of existing ones is a priority **[1, 2, 3]**. Biomass importance is underlined by Gallezot **[4]** by discussing research strategies for catalytic conversion to end products. By 2050, biomass resources are estimated to cover 15% - 20% of the world's energy demand **[5]**. This study reveals that energy crops account for up to 60% of the total biomass quantity, depending on cultivation land availability. In **[6]** the authors suggest that there will be an increase in usage of biomass crops because of economic, ecological and environmental advantages. Based on studies performed between 2006 and 2011, in Minnesota, USA, the work concludes that several energy crops species can be successfully exploited for energy production purposes. Herbert and Krishnan **[7]** present an assessment of potential and benefits that biomass generated energy can offer. This interesting study also discusses elements of pricing, regulations and control of emissions.

Short Rotation Coppice (SRC) plantations provide a beneficial option for biomass production while reducing the impact of wood industry requirements on domestic forest resources. A critical component of efficiency and cost effectiveness in SRC plantations is represented by two production chain activities: material harvesting and harvested material processing. The equipment used in these procedures can bring substantial productivity benefits. Evaluations of existing technological solutions and on-going research activities are presented in specialty literature.

Musshoff **[8]** provides a comprehensive evaluation of SRC plantations in Germany and advises on the cases when conversion to energy crops is advantageous. In **[9]**, Lechasseur and Savoie discuss development of equipment for harvesting, cutting and bundling, with the focus on some specific machines. The authors specify that this technology is still under development and presents future research directions. Krasuska and Rosenqvist **[10]** discuss the opportunity of energy crops development in Poland and underline that technology developments are important and contribute (on medium and long term) to cultivation cost reductions. Bender et al. **[11]** explain the benefits of SRC as suppliers of wood for energy and industrial applications. The authors suggest and mathematically analyze a model which includes uncertainties associated with SRC plantations. Studies regarding vibration influences in combine cutting platforms are evaluated in **[12]**. The authors present experimental results after testing on a John Deer 955 combine used in the harvesting phase. A prototype for harvesting of energy crops is described in **[13]**. The Biotriturator has been tested in Po Valley, Northern Italy and represents an effective solution for small sized farms. The authors advise on the need of further research and experimentation in order to develop machines with high-throughput at sustainable costs. Fiala and Bacenetti **[14]** discuss another solution for harvesting of poplar plantations. The Forager Claas Jaguar 880 is used in combination with the GBE2 header and an analysis of harvesting with this system indicates that it is efficient for plantations larger than 400 ha.

Y. Sun et al. **[15]** present a mathematical filtering procedure for correcting penetration resistance (PR) errors in agricultural activities. The study uses a bi-directional penetration method to calculate the penetration friction component (PFC) using a specially designed cylinder. An interesting material for developing prototype sensors used in soil mechanical resistance measurement is presented in **[16]**. Christy et al. **[17]** describe the main features of a software package that measures the dimensions and numbers of checks in scanned images of weathered wood surfaces. The application allows users to successfully quantify checking in a range of preservative treated wood specimens that have been subjected to natural weathering. Lamaming et al. **[18]** discuss mechanical properties of binder-less panels manufactured from raw material of young and old oil palm trunks while in **[19]** a set of DSP algorithms based on neural networks and used in the operation of a simulated biochemical reactor.

Specialty literature is focused on discussing new types of devices, machines, applications and studies which address different agricultural (including SRC) activities. This work proposes such a direction.

The goal of our work is to describe the automation and measurement performances of a prototype machine used in SRC plantations during the post harvesting phase. Specifically the process of cutting, sorting and bundling of harvested energy crops. The machine provides a viable alternative to manual labor providing increased processing speed and accuracy.

This device is part of the Rod Picker project **[20]** and is considered a prototype. The project has been developed with the collaboration of the following partners: Egedal Maskinfabrik AS - Denmark, Salix Energi Europa AB - Sweden, Lempe Gbr - Germany, TTZ Bremerhaven – Germany, TU Dresden – Germany and U.P. Timişoara – Romania. The Rod Picker project also includes a harvester which has been developed by TU Dresden and is not the purpose of this paper. According to the author’s knowledge, this type of device is unique. Initial development ideas and some prototype technical features have been discussed by Ionel et al. **[21]**. The present manuscript describes the final prototype version including new measurement, sensors and automation technology.

Two locations have been used for developing and testing the proposed prototype. The first location is in the city of Timişoara, Romania, in a laboratory belonging to the University Politehnica Timişoara. The second location is in Höfgen-Ketzerbachtal, Germany at the SRC plantation belonging to Lempe Gbr. During the testing and deployment at the beneficiary stages all project partners have been present for evaluating the performance of the prototype.

The remaining part of this paper is organized as follows: Section 2 presents an overview of the proposed system, the measurement operations and control elements are discussed. An evaluation of the benefits this machinery brings is also presented. Section 3 shows relevant experimental results. System functionality and accuracy features also are evaluated. The author’s conclusions, concerning both the functionality performance and the future developments are mentioned in the final section.

2. Materials and methods

2.1 Prototype operation principles

The energy species which have been used in our laboratory experiments were willow and poplar (Salix spp. and Populus spp.). On SRC farm testing has been performed for several weeks using willow. The tests began in January 2014, during the harvesting period. Testing has been extended in March 2014 in order to further evaluate the adjustments performed on some prototype functionality issues. In the case of last testing phase, our team used material which was initially stored by the beneficiary in January.

The proposed system was implemented with respect to clearly defined guidelines:

• An operator must insert harvested material rod by rod. The rods must be inserted with the thick ends first. Little intervention should be carried out while the prototype measures, cuts, sorts and bundles the rods.

• Each processed rod must have a diameter between 7 mm (minimum) and 25 mm (maximum). Also, the length of the rod will be between 1200 mm (minimum) and 2200 mm (maximum). These conditions must be fulfilled for all rods destined for bundling. Bundled rods will be used by Egedal planting machines. This is the reason for setting the specified limitation values.

• Resulting waste material (usually base and top parts of the rods) must be automatically sorted and placed in a container. This material is provided for subsequent shredding and is to be used as alternative fuel.

• Measured rods are destined for the packaging process: 50 rods when processing Salix spp. and 25 rods when processing Populus spp. However these values should be customized according to farm owner requirements.

• The prototype automatically measures all processed rods and must provide information regarding total length for each bundle of 50 rods. This information should be displayed on a screen and more details will be provided according to farm owner specific customization.

Figure 1 presents the functional prototype deployed at Lempe Gbr. This image shows the operator inserting rods in the cutting head. For a better understanding of the operation principle a view from the back of the process line is presented.

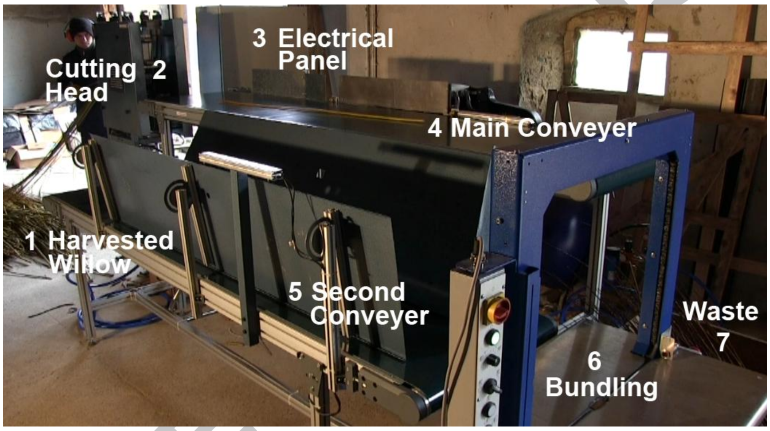

Figure 1. Prototype for cutting, sorting and bundling deployed at Lempe Gbr

The operation flow is described in the following steps. There is one operator which inserts the rods and bundles them after processing.

• 1 – Harvested material, willow. This material has been used for testing of the prototype in industrial conditions.

• 2 – Prototype cutting head. It is the first point of interaction between the user and the prototype. This component includes the majority of the sensors, knives and diameter and length measurement systems. The operator inserts the rods from the front of the machine. The back of the head ejects both waste material and processed rods.

• 3 – Electrical panel (seen from the back). It includes all control elements, electrical connections, display and operation switches.

• 4 – Main conveyer belt. It is used to transport material and for sorting purposes. In Figure 1, one can notice the willow rod traveling on the conveyer. This belt starts functioning from the moment when the operator begins inserting rods. Once the desired number of processed rods reaches a set value (for example 50 rods for willow), the conveyer stops to indicate that bundling must be performed because the package is complete. From this conveyer, rods are directed towards the second conveyer (if rod obeys measurement restrictions) or towards waste material storage.

• 5 – Second conveyer belt stores rods cut according to diameter and length imposed restrictions. This conveyer does not operate until the set number of 50 rods per package has been reached. At this moment, it automatically pushes all material towards the bundling machine (Mosca Strapping Machine).

• 6 – The bundling machine is used by the operator manually. This is the second point of interaction between the user and the prototype. These packages will be placed in special cases and delivered to SRC farms for planting purposes.

• 7 – Waste material is stored in a case.

2.2 Measurement and Automation Components

The prototype is supplied by three phase electricity. The BeltAir Pro Ceccato compressor provides necessary air for driving several pneumatically. The cutting head includes the majority of the sensors. Figure 2 describes the automation process together with the technological characteristics. This image shows the general hardware structure of the cutting and control system.

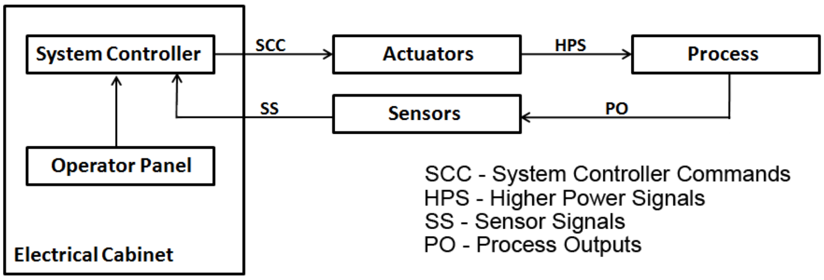

Figure 2. Schematics of the hardware structure for the Cutting and Sorting Control System

The Process is represented by all mechanical and pneumatic components. The automation process is monitored by the System Controller (the SIEMENS S7-1200 PLC) located in the Electrical Cabinet. System Controller Commands (SCC) are used to communicate with all Actuators. They are represented by motors, drivers, amplifiers, relays or inverters. Actuators turn control signals into Higher Power Signals (HPS). The Process Outputs (PO) are read by different Sensors which transmit these signals to the System Controller. Finally, the operator is able to interact with the system using the Operator KP300 Monochrome Panel.

The Actuators are: the Main Motor (Siemens, 1FL-5060) used to move the rod trough the cutting head, the Sinamics V60 Motor Driver, two motors with inverters for moving the conveyer belts, the cutting blades with corresponding electro-valves and pneumatic control and the pneumatic eject system used to separate the rods.

Several sensors have been used to perform required measurements. These sensors mainly rely on optical technology and they are all designed for industrial usage.

The Omron ZX GT smart laser is the most important measurement component and it is used to measure the rod diameter. This sensor is located in the cutting head. Note that the rod is directed trough the laser curtain. This curtain is 28 mm high and since a maximum diameter of 25 mm is required, one has to ensure that the rod position is not subjected to high amplitude movements when taking the measurements. Processing of measured values is done real time and the algorithm is included in the control software. The result of this calculation is a condition for cutting triggering.

The rod length is determined using a Omron E6B2-CWZ5B rotary encoder fixed on one of the grabber wheels. Processing of encoder pulses generates a real time measurement of the length. This parameter is correlated with the diameter measurement to trigger the rod cuttings.

Several other optical sensors have been used to monitor the rod positioning at different time intervals.

The Omron E3X area sensing fiber is located at the output of the cutting head. This sensor signals when the rod is set in the correct initial position so the measurement can start. A first cut will be triggered by this sensor. This cut will remove 3 cm from the thick end. These rod pieces are considered waste material.

Sensors like the Omron E3JM-10M4-G-N are placed on the conveyers and on the bundling machine. These elements indicate when the rod has reached a certain point and trigger the operation for waste material separation. They are also used to indicate when the bundling procedure can start.

Figure 3 shows the front view of the prototype (left) and different sensors placed along the processing line (right).

- 1 – Cutting blade which is controlled by the System Controller via pneumatic pistons (3).
- 2 – Safety element and laser sensor functionality indicators. A green Led light indicates when the operator can insert a new rod.
- 3 – Pneumatic pistons and electro-valves for controlling the blades.
- 4 – Operator panel for monitoring different values like the number of processed rods or total length.
- 5 – Front view of the electrical panel.
- 6 – Waste material from the first cut is stored in this case.
- 7 – Laser module Omron ZX GT measuring the rod during experimental testing.
- 8 – Light barrier next to air nozzles of the sorting system.

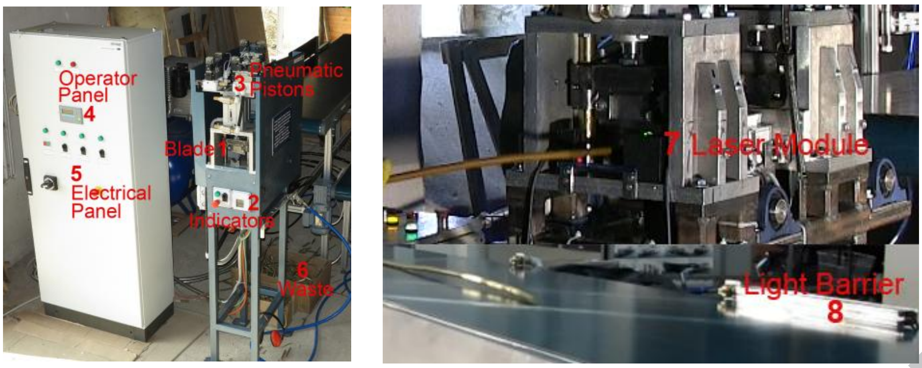

Figure 3. Prototype front view (left) and different sensors placed on the processing line (right)

2.3 The Control Algorithm

The control algorithm is implemented as a State Machine structure and runs on the System Controller. Figure 4 shows the schematic structure of the final software version. This image corresponds to the situation when bundling packages contain 50 rods.

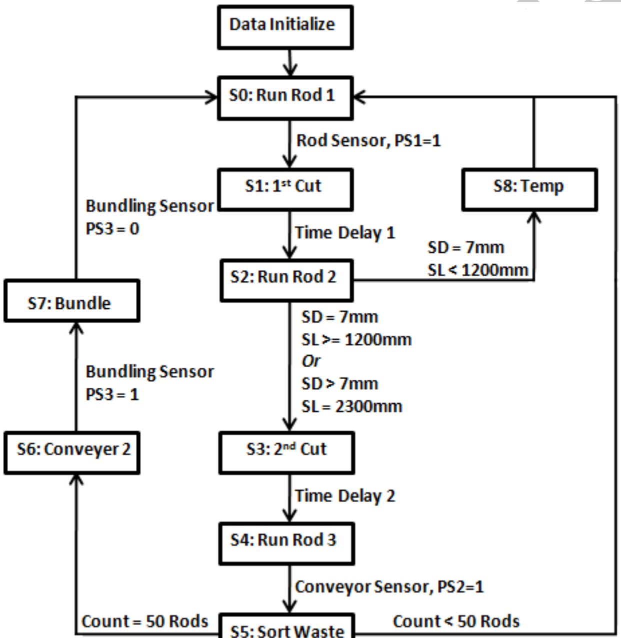

Figure 4. Schematics of the State Machine structure for the control algorithm

For clarification purposes the following notations for the system actuators and sensors are considered:

- Actuator 1 (A1) – Siemens Motor and Sinamics V60 inverter for rod moving in the cutting head.
- Actuator 2 (A2) – Motor with inverter for main conveyer.
- Actuator 3 (A3) – Motor with inverter for second conveyer.
- Pneumatic Knife (PK) – Cutting Knife actuated by a pneumatic piston.
- Pneumatic Blower (PB) – Air blower used to select good rods from waste material.
- Length sensor (SL) – Previously described encoder.
- Diameter sensor (SD) – The laser measurement system.
- Light barrier (PS1) **-** Senses the presence of the thick rod end and triggers the first cut.
- Light barrier (PS2) **-** Senses the presence of the rod on the main conveyer and triggers the waste separation.
- Light barrier (PS3) **-** Senses the presence of the rods on the bundling machine and signals when the bundle has been removed.

After Initialization of all system variables, the prototype waits for rod insertion (S0 state). At this moment A1 is running and the transition to the next state is triggered when PS1 is active. This means that a new rod has been inserted.

A new rod insertion can be performed in different situations: at the beginning of the operation, if the bundling has been performed and the corresponding sensor indicates that the bundling machine is free (S7 state); if the rod counter has not reached the target value of 50 rods; if the last processed rod has a diameter of SD = 7 mm however the length is SL < 1200 mm (from S2 state). If the last situation occurs, it means that the previously cut rod is not suitable for selection and will be considered waste material. S8 was introduced only for flow.

S1 is reached when PS1 signals that the thick end of the rod is in position and it must be cut. For this procedure A1 is stopped, PK is activated and Timer 1 is started. Transition to S2 is done after the Timer 1 has elapsed.

S2 is the state when all measurements are performed (SL and SD are monitored) and the rod characteristics are compared against imposed restrictions. The algorithm transitions to other states (S3 if rod is accepted and S8 if rod does not fit imposed restrictions).

S3 is used to perform the second cut. This cut is performed towards the thin end. For this operation A1 is stopped, PK is activated and Timer 2 is started.

In the S4 state the rod is already traveling on the main conveyer. So the rod was pushed (via A1) from the cutting head towards the main conveyer. A2 is also running. If PS2 is active this means that the rod has reached the point of waste separation. The separation is performed in S5.

In S5 the pneumatic air blower PB is activated only if the rod characteristics are within imposed limitations. In this situation the air flow will push the rod on the second conveyer. If the rod is not within imposed restrictions it will not be selected. Since it is considered waste material it will travel on the main conveyer and fall in the corresponding case (see Figure 1, component 7).

S6 corresponds to the second conveyer. At this moment, 50 rods have been selected. This means a bundle can be performed. A1 is automatically stopped. So the operator cannot insert a new rod. Consequently the operator knows that 50 rods have been cut and a bundle should be done. A3 is started so the 50 rods are automatically pushed inside the bundling machine.

S7 is dedicated to manual bundling. PS3 indicates that the 50 rods are in the bundling position. All other motors are stopped. The operator goes to the bundling machine and pushes a button which will trigger the bundle. At this moment a 50 rods package is ready so the next 50 rods can be processed.

2.4 Economical perspective of the prototype

This machinery is a prototype and it has been subjected to different changes and adjustments during the entire implementation period. The purpose of this project was to develop the functional machinery and this was agreed by all partners. Evaluating and lowering the costs of this machinery in the production flow remains to be considered for a future project. Machine use and depreciation of the components, costs for housing, operator and maintenance have not been included.

Materials and components used for developing this prototype (Omron ZX GT smart laser system, sensors, actuators, PLC, encoders, light barriers, cylinders, electro-valves, cutting blades, metallic guidance, wheels, structures etc.) reached a total cost of approximately 70000 €. This value does not include personnel and development costs. This price includes other components which have played a part during the prototype development process (or are used for maintenance purposes) and are not physically present on the deployed machine.

The final product for which this machine was developed is represented by a SRC box which contains 5000 m of processed material (see Figure 7). For Lempe Gbr, the price of such a SRC box is approximately 2000 €. This means that the price per m is at 0.4 €. In general, the price per SRC cuttings fluctuates between 0.04 € and 0.25 €, as reported in specialty literature **[8, 10, 22]**.

Referring strictly to the process in which this machinery is involved, during the testing phase it has been evaluated that the cost for producing one SRC box is approximately 50 €. This value does not include costs for other operation in the chain (Preparation and Plantation, Harvesting, Transportation, Tending Strategies and Storage). This value is smaller when compared against the price of manual labour for cutting, sorting and bundling. We have considered a 10 € per hour payment for a seasonal worker in Germany. Using 6 workers, during an 8 hour workday, 2 boxes are completed at a total cost of 240 € per box. *This is approximately 5 times more expensive than the work using the proposed system.* These numbers are based on a 5 year evaluation calculated by Lempe Gbr and they are consistent with what is presented in **[23]**.

It has been concluded that the prototype presents an economical perspective. Operation prices are lower than the ones obtained when using manual labor. Production times are faster, fact which will be underlined in the next section. Implementation costs should be considered as guidelines since a lot of effort has been engaged in the machinery development. Series production could dramatically lower these costs. If we estimate a production price of 50000 € (machinery and implementation work), at a price of 2000 € per box the farmer would have to sell 25 boxes to break even. At an average rate of 5 boxes per ha it only depends on how many ha are harvested. However, in the case of 5 ha per SRC farm, the machinery can process in a year all 25 boxes.

3. Experimental results

The proposed prototype was developed and tested under laboratory conditions at University Politehnica Timişoara, Romania. The second test location was in Höfgen- Ketzerbachtal, Germany at the SRC plantation belonging to Lempe Gbr. The laboratory tests have been performed during several months, before deployment at the second location. A short film presentation can be accessed at **[24]**. Testing in actual industry conditions has been performed in January and March 2014. The machinery has been continuously operated and monitored for several hours per day for a total of three weeks.

Our team followed several objectives during the testing phases. The most relevant are specified:

• The proposed automation solution should correctly function without errors in the process flow. The user intervention for maintenance purposes should be minimal.

• The efficiency of the machinery when discussing execution time and processed material quantity should be satisfactory when compared against manual work outcome.

• The cutting accuracy of the system should be within limitations imposed by the project partners and help in reducing the quantity of material which is lost because of erroneous hand-made measurements.

• Evaluation of numeric results related to the cutting process should be handled by the system and presented to the user on an operator panel.

The presence of ice and mud along the length of the rods has been a critical issue. This fact can introduce errors in the diameter measurement process. The laser system could report a diameter value larger than the actual one. This may trigger a cutting in an erroneous position. Optical sensors may be affected by drops of mud present on the lenses. Lens cleaning with an air pistol (included in the machine) was necessary after several hours of operation. Icy material sometimes slipped between the grabber wheels thus introducing length measurement errors. A future development of the machine includes introduction of modified grabbing wheels for avoiding material slipping.

Another important testing factor has been the correct setting for the air nozzles of the sorting system. A higher pressure would cause the cut rod to be blown over the second conveyer. On the other hand, too little pressure would cause the rod not to be sorted thus ending up in the waste material case at the end of the line. During laboratory conditions, using dry rods, the following weight values have been recorded: 1200 mm dry willow in the range of 43 g - 45 g, 2200 mm dry willow in the range 125 g - 128 g, 2300 mm dry willow in the range 134 g - 140 g. On Lempe Gbr site the following weight values were recorded: 1200 mm wet and muddy willow in the range 47 g - 49 g, 2200 mm wet and muddy willow in the range 145 g - 148 g. The pressure setting was adjusted in a range of 150 kPa and 300 kPa.

3.1 Production performance evaluation

The working environmental temperature range was between -6°C and +10°C. As testing material freshly harvested Salix willow (see Figure 5) has been used. The rod dimensions were at a maximum 35 mm diameter and a length which fluctuated around the value of 3 m. Some rods presented smaller additional branches which need to be stripped by the operator before insertion. However, this procedure does not affect the machine execution performance and must be done for less than 5% of the rods.

Figure 5. Test material at Lempe Gbr

Figure 6 (left) presents manual procedures for cutting, sorting and bundling of rods. For the proposed prototype, on site testing was performed with a single operator on the system. Figure 6 (right) presents the operator when inserting a rod in the cutting head. In this case, one person is responsible for inserting the rods, cleaning the laser system and bundling the processed material.

Figure 6. Manual (left) and automated (right) cutting, sorting and bundling of harvested material

The presented automation approach is capable of meeting the imposed performance by producing 1 bundle of 50 rods in approximately 7 minutes, with one person operating the device. This means 8 bundles per h or approximately 800 m of processed material per h considering an average length of 2 m for each rod. *For our partner (Lempe Gbr), the contents of a standard SRC box includes 5000 m of material. This is delivered to customers.* When using the proposed prototype, the contents of a SRC box can be delivered in less than one working day. This is achieved with a single processing line operated by one person. Based on the experience of Lempe Gbr owner, using manual labour, 3 people deliver 1 box of processed material in one working day. However, manual operations introduce total length measurement errors which are compensated by adding extra bundles in the boxes. This issue will be analysed in the following section.

If the proposed system is expanded to more processing lines, 3 operators could deliver 3 boxes of material in a single working day. This operation requires a cost analysis which must be discussed for each particular SRC plantation.

Figure 7 shows rod bundles which have been cut according to diameter and length restrictions (discussed in Section 2.1) using the proposed processing prototype. On the right, several bundles placed in one storage box can be seen. Each bundle can be tied in two or three points. During the testing phases the limits of the cutting points were adjusted to different values. These tests have been necessary in order to confirm the control algorithm functionality and to present that diameter and length limitations are adaptable, that the machinery is customizable.

Figure 7. Cut, sorted and bundled harvested material using the proposed prototype

3.2 Measurements accuracy evaluation

The most significant performance of the proposed system is the cutting accuracy. When using manual labour, in each delivered box extra bundles of material were added in order to compensate for measurement. Consequently, a special task of our team was to deliver a system which considerably reduces the length measurement errors.

The accuracy of the proposed system is discussed using experimental results from Tables 1 and 2. These values have been obtained during a final performance evaluation together with Lempe Gbr representatives.

Table 1 presents the *length characteristics of 20 randomly chosen rods after being measured and cut with the proposed system*. The *relative measurement error* has been considered as the relevant indicator. For each calculation we observed the automated measurement result (presented on the *KP300 Monochrome Panel*) and then manually measured the rod. Manual measurements have been performed using a measurement tape.

The column entitled *Automated Meas. (mm)* presents values indicated by the machine. The next column, *Manual Meas. (mm)* shows the values obtained by manually measuring each rod. These values have been considered as standard true values. The next column is the relative error value. Finally, the *Evaluation against imposed values* column is relevant because it indicates the maximum deviation from imposed values (see Section 2.1).

The relative error column, $\varepsilon_{\%}$, shows in the majority of cases a difference of under ±2% (value defined by the project partners) between what the machine measures and the manually measured length.

Table 1. Accuracy evaluation for length measurements for individually randomly chosen rods

Rod	Automated Meas. (mm)	Manual Meas. (mm)	$\varepsilon_{\%}$	Evaluation against imposed values
1	2220	2225	0.225	25 mm outside imposed limitation
2	1780	1785	0.280	Within limits
3	2230	2225	-0.225	25 mm outside imposed limitation
4	2220	2230	0.448	30 mm outside imposed limitation
5	1540	1560	1.282	Within limits
6	2220	2220	0	20 mm outside imposed limitation
7	1520	1540	1.299	Within limits
8	1810	1840	1.630	Within limits
9	2000	2000	0	Within limits
10	1580	1590	0.629	Within limits
11	2200	2230	1.345	30 mm outside imposed limitation
12	2220	2220	0	20 mm outside imposed limitation
13	1740	1840	5.435	Within limits
14	2220	2220	0	20 mm outside imposed limitation
15	2230	2215	-0.677	15 mm outside imposed limitation
16	2230	2220	-0.450	20 mm outside imposed limitation
17	1830	1840	0.543	Within limits
18	1400	1410	0.709	Within limits
19	1640	1630	-0.613	Within limits
20	2210	2220	0.450	20 mm outside imposed limitation

For example, if we consider Rod 4, the machine measures and cuts it at 2220 mm. So there is a 20 mm error when reading the info from the KP300 panel. However, when the same rod is manually measured (when manually measured it was held as straight as possible) we obtain 2230 mm. The value of “30 mm outside imposed limitations” presented in Section 2.1. For this particular Rod, there are 30 mm of extra material after cutting. When reported to the 2200 mm, this value represents only a deviation of 1.36%. If the Rod length does not fall outside the imposed interval, the column specification is *Within limits*.

The relative error values $\varepsilon_{\%}$ are calculated because we looked for a measure of difference between what the machine indicates and what is the actual rod length when held straight and manually measured. In the majority of the cases, these values are actually lower than the ±2% target. This error is caused by different factors like ice and mud presence along the rod length, rod irregularities or curving. Also, the fact that the rod has not reached the minimum diameter but has reached the maximum allowed length is a cause for a slight delay in the cutting procedure.

The same discussion applies to Rod 1. It was cut by the machine and the indicated length was 2220 mm. When manually measured, the length was actually 2225 mm. So this shows a deviation of 25 mm from the required 2200 mm and a deviation of 5 mm from what the machine indicates. Overall, this particular rod introduces a 1.136 % length measurement when compared against the 2200 mm limit. The relative error is 0.225.

For rod 13 the relative error is higher. This case is one of the few which have been observed. How it affects the length of the entire bundle will be discussed using data from Table 2. Out of approximately 150 individually measured rods, a relative error outside the ±2% interval has been observed in 8% of the cases. For all these situations, the observed values did not fall outside ±6%.

The cutting effects on rod quality parameters (for example particle size distribution due to cutting) were not the scope of this work **[25]**. But nevertheless, observations during this study confirmed that the cuts at both ends are clean and do not present any sign of waste material.

Figure 8. Cutting quality on willow (left) and poplar (right) rods

Table 2 reflects the *measurement accuracy of 10 randomly chosen 50 rods bundles*. The accuracy of the proposed system falls within imposed limitations. Looking at the values recorded for Bundle 1 one notices that the machine indicates that this package (50 rods) has a total length of 104.10 m. After manually measuring each rod and adding the results, the total package length was 104.83 m. So there is an extra 0.73 m of material in this package.

Assuming that in a 5000 m of material box, all bundles resemble the characteristics of Bundle 1, the prototype indicates that 48 bundles are needed. The actual length of the material in the box will have an extra 35.04 m because of the introduced measurement error. For the customer this means that he will receive the ordered material quantity and a small extra amount. So the introduced error is not in the customer disadvantage. Also, for the farmer, the total extra quantity introduced by the machine error is much lower (approximately one third of a bundle) than the one introduced to compensate for manual work measurements (usually two - three bundles).

Table 2. Accuracy evaluation for length measurements for randomly chosen bundles

Bundle	Automated Meas. (m)	Manual Meas. (m)	Extra Material (m)	ε%	Evaluation
1	104.10	104.83	0.73	0.696	Under ±2% error
2	104.58	104.79	0.21	0.200	Under ±2% error
3	99.73	98.57	-1.16	-1.177	Under ±2% error
4	100.69	101.87	1.18	1.158	Under ±2% error
5	103.65	103.78	0.13	0.125	Under ±2% error
6	104.25	104.84	0.59	0.563	Under ±2% error
7	104.85	104.92	0.07	0.067	Under ±2% error
8	104.36	104.5	0.14	0.134	Under ±2% error
9	103.88	104.1	0.22	0.211	Under ±2% error
10	100.05	101	0.95	0.941	Under ±2% error

Bundle 3 is a special case when the machine indicates more material than the package actually contains. In this case, with each bundle a shortage of 1.16 m of material is observed. In order to fill a 5000 m box the machine will indicate that there are 51 bundles needed. Assuming that in a 5000 m of material box, all bundles resemble the characteristics of Bundle 3, there will be a shortage of 59.16 m. In this case, the customer is in disadvantage. However one needs to consider that erroneous measurements like the ones performed for Bundle 3 have been reported once for a series of 20 Bundles. Consequently, delivering less material in a 5000 m box is not a feasible assumption.

A statistical analysis of measurement results obtained when using the proposed automated solution indicates the following. Out of 150 individually manually measured rods in 12 cases an error greater than ±2% has been recorded. In all cases, the difference between automated and manual measurements was smaller than ±6%. When reported to the maximum length of 2200 mm, a difference of approximately 132 mm was an extreme case. Causes for such results have been previously presented. When discussing 50 Rods bundles, in only 5% of the cases a quantity smaller than the one indicated by the prototype, has been recorded. Table 2 shows that the end user will receive an extra quantity of material. For the producer, this loss is approximately three times smaller than what manual operations (presented in Figure 6 - left) cause.

Another aspect which is flexible on the proposed system is the user data presentation. The operator interacts with the KP300 Monochrome Panel and receives information about number of rods which have been processed and the total length. After each bundle these values are recorded. At the end, the operator knows the exact length of all bundles so he can evaluate the contents of a box.

Experimental results show that the proposed prototype system performs as expected. It is easy to use (one operator per line), provides all necessary information and can be expanded to more processing lines. Regarding the measurement and cutting accuracy, the calculated length values are within imposed limits. Although for this project length and diameter restrictions have been fixed, using minor software adjustments the rod processing conditions are fully customizable. The authors consider that the high-throughput of the device can drastically reduce SRC processing times after the harvesting phase.

4. Conclusions

The automation component and industry conditions performances of a prototype machinery designed for cutting, sorting and bundling of SRC material for planting purposes has been presented. This project is the result of collaboration between six partners from four different countries and has been tested as part of a SRC production chain. Although adapted to willow and poplar (Salix spp. and Populus spp.), this technology is still under development presenting promising research directions. The benefits of the proposed system come into play after the harvesting phase. Testing material has been automatically cut according to imposed diameter and length restrictions. However, if required, the machine can be customized to work with different rod characteristics. Resulting bundles have been measured in order to validate device accuracy, this being one of the most important operation characteristics. The authors consider the prototype as an innovative solution which uses state of the art measurement and control solutions in order to deliver rapid SRC processing. It has been demonstrated that the presented machinery operates correctly and within the accepted accuracy limitations.

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HIGHLIGHTS

- Presents prototype for cutting, sorting and bundling of harvested energy crops.
- Discusses the automated preparation of cuttings for planting purposes.
- Was tested in laboratory and industrial conditions using Salix and Populus spp.
- Experimental results demonstrate the efficiency and accuracy of measurements.
- Cutting conditions can be customized according to user requirements.