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Review

Recent Contributions of Some Fields of the Electronics in Development of Forest Operations Technologies

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Abstract: In the last years, there has been a growing need to improve forest-wood chain concerning all three pillars of sustainability (economic, environmental, and social). Using electronic systems, in particular GIS, GNSS, and various kinds of sensors related to forest harvesting, is clearly one of the most powerful instruments to reach this aim. The contribution of these tools to forest operation is wide and various. One of the most important application was integrating ICT and GPS/GNSS on-board systems on modern forest machines. This allowed one to ensure multiple benefits to forest operation field. On the one hand, electronic systems, and particularly GIS, could be used to improve forest harvesting with a previous planning of the skid trails network, in order to minimize utilization impacts and risks for operators, ensuring at the same time high work productivity. Moreover, GIS developed files could also be implemented in modern forest machine GPS/GNSS systems, helping forest machines operators to move only along a designed skid trails network or making it possible to avoid restricted access areas. On the other hand, modern forest machines could be equipped with complex and accurate sensors that are able to determine, register, and share information about wood biomass quantity and quality and even undertake economic evaluation of stumpage value. Finally, the input and output of these systems and sensors could be implemented in a decision support system (DSS) ensuring the best silvicultural and operative alternative from a sustainable forest management point of view. A detailed review of the contribution of electronics in the development of forest operations is provided here.

Keywords: electronic devices; GIS; GNSS; sensors; sustainability; productivity

1. Introduction

The growing interest in environmental and social services of forests has led to an increase in the importance of the forest world but also to a greater complexity of its systems [1].

This becomes even more important considering the changes that the European forest sector has undergone in latest years. In the last two decades, recent innovations in harvesting methods have been combined with electronics science in order to improve techniques for forest operations. Electronic systems are integrated into forest machinery to produce optimized performances with less energy use, a cleaner environment, and greater wood utilization. This allows the reduction of harvesting costs and increased yields for forest enterprise and the wood processing industry. The latest technology makes sustainable forestry and ecosystem management possible during harvesting, roading, and transportation, over the full lifecycle of a forest. In particular, recent advancements have led to an increase in employment of analytical and communication tools in forestry, concerning data from satellite, airborne, unmanned aerial vehicles, global positioning systems, and many sensors, devices, and other informatic tools [1]. For this reason, precision forestry, and all other sectors related, can represent the new direction for a better forest management; in fact, this approach is focused on information and supports economic, environmental, and sustainable decisions by using high technology sensing and analytical/digital tools. Thanks to this progress, modern technological systems in forest operations (tree felling, bunching processing, and wooden material extraction), called precision forest harvesting, can supply powerful instruments to reach the important aim of sustainable forest management. This term condenses a multi- disciplinary and inter-disciplinary concept, which provides an integrated use of new technologies, in order to obtain innovative solutions for specific issues in the forest sector [2]. In addition, the international community has demonstrated that forestry operators have globally begun pioneering the use of advanced technologies to improve forest-management results. The diffusion of electronic systems and tools in many forest contests and different modalities, such as software, instruments, machinery, and portable devices, provided many advantages to foresters, forest owners, and also to the wood processing industries. Starting from ecological benefits of increased productivity, there is also an economic and social value to consider. Modern electronic technologies allow quick and direct communication among single forest operations and improve the quality of work.

The main instruments provided by precision forest harvesting, analyzed in the present review, can be grouped in three main categories: GIS applications, GNSS instruments, and machine sensors. Modern forest machines like harvesters and forwarders are equipped with all these instruments [3], which allow for environmentally friendly forest utilization with high work productivity and in safe conditions for forest workers. It is important to underline that precision forestry is not only related to these instruments, but there are also many other ones, which are very important, and which have been deeply analyzed by scientific literature in the last years. Examples could be airborne laser scanning or unmanned aerial vehicles, which represent other fundamental instruments of precision forestry. However, we did not take them into consideration in the present review mostly for two reasons. Firstly, because scientific literature is so wide on these topics, they would deserve a dedicated discussion and, secondly, because at the moment, these instruments' use is mainly linked to biomass estimation and impact analysis; instead, our focus with this review is only on operative yard phase, from the starting of operations, up to their end on landing site. One of the prerequisites of sustainable forest management (SFM) is in fact to minimize the negative impact of harvesting on the environment without limiting work productivity [4–6]. Considering this as a review focused on particular electronic instruments like GIS, GNSS, and sensors linked to the operative phase of a forest yard, could turn out to be very interesting for the reader.

After reviewing the large but scattered amount of publications on the subject, this paper brings together in-depth knowledge and insights of experts, under an integrated and comprehensive framework. The focus is set on the most recent scientific research, conducted throughout the 2013–2019 period.

First, a perspective of the state-of-art about the three main instruments of precision forest harvesting (GIS, GNSS, and forest machine sensors) is provided. After that, a brief overview is given on the possibilities of precision forest harvesting usages, with a focus on the possibilities of smartphone applications. This latter aspect is particularly important concerning Mediterranean Region, where the major part of forest enterprises are still small family businesses, therefore even if they cannot afford modern forest machines, they do, however, have the possibility of improving their work thanks to innovative technology.

Finally, the future perspectives and possibilities of improvement are reported.

2. Materials and Methods

Literature Search

One of the basic techniques for searching in complex database is using the Boolean operators. Boolean searching is a symbolic logic system that creates relationships between concepts and words. Systematic reviews through Boolean searching allow one to analyze all studies in a specific research field, so it is particularly suitable to search papers for a scientific review on a specific topic. The research was performed using the databases Science Direct, ISI Web of Knowledge, and Google Scholar. The first step consisted in using the search string "Precision Forest Harvesting" like "Precision Forest Utilization", "Technology Assisted Forest Utilization", and "Technology Assisted Forest Harvesting". After that, three specific categories (GIS, GNSS, and electronic sensors) were developed; these categories were selected on the basis of their highest weight in comparison to other ones. Total findings of this research, without any temporal restriction, were over 57,990, while referring the research to the last five years, over 34,140 findings appeared (Figure 1). It is important to underline that about 60% of findings were published in the last 5 years, thus demonstrating the great activity of scientific research on these topics.

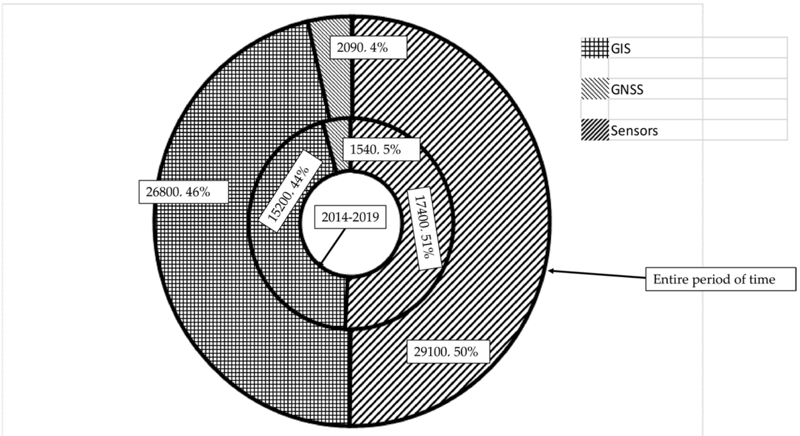

Figure 1. Specific detail for category referred to the Boolean search on specific databases.

Obviously, most of them were not completely related to the addressed topic, and for a proper scientific sound, we selected papers published in journal with specific bibliometric indices, related to the categories "Engineering", "Computer science", and "Forestry" with ranking Q1, Q2, and, only in cases of specific relevance for the topic, ranking Q3. The second phase of our methodology consisted of refining our research using only Scopus database. The research strings used were: "Forest Harvesting" AND "GIS", "Forest Harvesting" AND "GNSS", and "Forest Harvesting" AND "Machine Sensors". In a subsequent phase, we also used research string "Forest Harvesting" AND "Smartphones" but there were only few findings and so in the present review only a short overview of use possibilities of these instruments to improve forest operations is given. According to what is written above, an amount of about 100 papers that referred to the last five years was analyzed, focusing on the main results and evidences on GIS, GNSS, electronic sensors, and, secondly, smartphone contribution to forest utilization improvement.

Another important consideration is that, given the peculiarities of the investigated topic and the strong links existing among the analyzed electronic instruments (just think to the correlation between GIS and GNSS), some papers were about not only one aspect, but multiple ones. In such cases, we inserted the paper in the section that the original article mostly focused on.

3. Results

In order to gain a logic scheme of presentation, the results were categorized in four main macro areas: GIS applications, GNSS instruments, machine sensors, and smartphone applications. However, the high complexity related to the science of electronics and its applications makes it difficult to have a clear differentiation about the four macro area selected. For these reasons, it is clear that some aspects were cited and treated many times in the four areas but framed from different points of view. Then, for each area, when possible, some examples of applicative cases were shown, as well as levels of accuracy achieved by these applied technologies and their contribution to the sustainable forest management. The general focus, common between the four macro areas, was on carrying out forest operations in a sustainable manner, based on the new concept of sustainable forest operations (SFO) [7]. This concept provides integrated perspectives and approaches to effectively address ongoing and foreseeable challenges related to the forest management, and in this perspective, electronics seems to be an increasingly valid ally.

3.1. GIS Applications

GIS applications in the forest sector are vast and diverse [8]. Typically, the GIS allows a range of application from essential functions for spatial analysis to the application and development of statistical and mathematical modelling [9]. In terms of forest utilization, the most important functions, which have been widely and variously explored, are focused on forest road network planning and aimed to support the identification of the most suitable harvesting systems or the evaluation of forest accessibility [8]. Slope, roughness, and several other morphological parameters, for example, may present significant spatial constraints for enterprises especially when high-quality stands of timber are located at considerable distances from existing logging roads. Such problems are aggravated during poor economic conditions, as forest companies may not be able to access the quality of timber required to maintain profits [10]. In recent years, multiple studies have shown the advantage of precision forestry and the use of geographic information system (GIS) in forest road network analysis and planning [11]. This new approach allowed to further stress the forest road multifunctional aspects; in this direction, a recent paper highlighted like the combination of GIS-multiple-criteria decision-making (MCDM) [12] approaches can properly assist forest road planning for forestry and touristic purposes [13]. One of the first GIS applications in forest road planning was the determination of mean extraction distance considering the actual forest road network. Thus, it was possible to assess and plan the most suitable extraction system focusing on the minimization of the total costs of timber extraction. Enache et al. [14] and Duka et al. [15] developed different GIS models to calculate extraction distance, including correction factors to consider road sinuosity and slope variation.

Another interesting GIS application is possible in the designing of a planned forest road network, considering various environmental and logistic parameters. In recent years, Enache et al. [16] used GIS and multi criteria analysis (MCA) in Romania, to identify an optimal road network considering management, costs, environmental, and social factors. The developed model was then tested and validated. A reduction of mean skidding distance from 864 m to 255–268 m was reported, leading to an increase in productivity of timber extraction from 7.5 m^3/h to 11.7 m^3/h and to an increased contribution margin from 21.2 €/m^3 to 25.1 €/m^3. Enhancement of forest infrastructure reduced CO_2 emissions due to timber harvesting and transport from 8.52 kg/m^3 to 7.3 kg/m^3. The integrated GIS and MCA is one of the preferred tools for the correct forest management for assessing the relative importance of the economic, environmental, and social criteria. In particular, the GIS approach is necessary in sites where it is fundamental to encourage the creation of a biomass supply chain network. In fact, a low economic value of biomass stock allows no room for incorrect choices concerning trails, location of energy plants, and logistical transportation. The importance of a correct optimization to reduce transportation costs is highlighted by several studies published over the past decade [17–22].

Another GIS model to automatically design skid-trail networks in order to reduce skidding costs and soil disturbances was implemented by Contreras et al. [23]. This model simulates tree-bunch locations, creates a feasible skid-trail network across the harvest unit, estimates skidding cost and soil recovery cost for each skid-trail segment, and finds the best network design that connects each tree-bunch to landings, reducing both skidding and soil recovery costs.

In forest road network planning, GIS could be even more efficient if integrated with other technological instruments such as linear programming. A new skid trails pattern developed in this way resulted in a 16.4% increase of work productivity, 44% reduction of skid trails length, and 44.29 ton/ha of prevented soil losses, compared to not-planned interventions [24].

Finally, concerning forest road network planning, Parsakhoo et al. [25] demonstrated the efficiency of GIS-planned skid trails networks also in close-to-nature forestry interventions, consisting of little interventions with low biomass removal, which are mostly applied in protected areas. In this study, a skid trail network was developed to extract marked trees from stand sites to landing sites using a GIS-based decision support system (DSS). The techniques were applied in a stand where single trees are felled in close-to-nature conditions. Results showed that on average the length of the route decreased by 6.65% to 19.22%.

An example of the efficiency of GIS in forest operations planning is given in Figure 2, which is a real application by the authors of precision forest harvesting in a Central Italy turkey oak coppice forest yard, utilizing the methodology proposed by Picchio et al. [11]. In the above-mentioned figure, it is possible to see the great difference in terms of skid trails number and length between a GIS-planned (Figure 2b) and a not-planned (Figure 2a) yard.

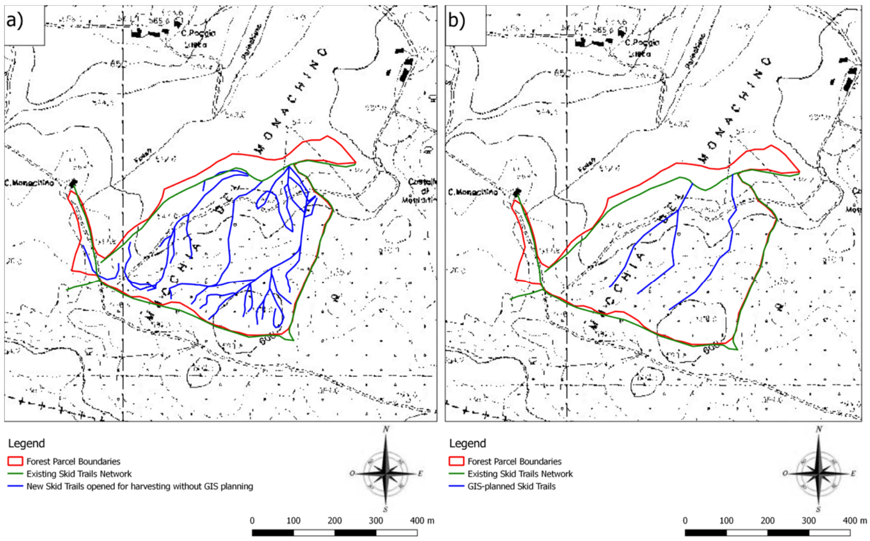

Figure 2. (**a**) A real skid trails network opened in a forest yard with no previous bunching-extraction planning. (**b**) The same yard with a geographic information system (GIS)-planned skid trails network. As It is possible to see in (**b**), there is a strong decrease of skid trails branches with positive influence from economic, environmental, and social (workers' safety) points of view.

The subsequent step of GIS application in forest utilization is aimed to plan interventions considering both road network, environmental, and topographic conditions of the area. This implies the concept of "Accessibility" or "Openness". That is, considering the peculiarity of a forest estate/parcel, (i) is it possible to access the forest in order to harvest wood material? (ii) Which machinery is more suitable for this?

The first scientific work with this focus was implemented last year by Synek and Klimanek [26], who developed a GIS model that indicates the most environmentally friendly extraction system, considering topographic, climate, machine equipment, and stand characteristics.

In 2016, Laschi et al. [27] devised a GIS approach to classify a forest ownership according to three accessibility classes: Accessible, barely accessible, and not accessible. In this study, the concept of accessibility was designed according to the time needed to reach a specific point in forest ownership starting from the actual forest network.

However, according to forest harvesting management, a concept of accessibility based on time criterion is less reliable than one based on distance from the existing road, even better if this distance is a "real distance", calculated considering slope instead of a horizontal distance [28].

One of the most recent papers that used GIS to classify a forest ownership in Turkey, according to the distance from existing roads, and so identifying the most suitable extraction system according to this distance, is Caliskan et al. [29]. The authors developed a model for timber extraction systems analysis, considering terrain morphology and, secondary, forest road network. Chainsaw–small-size cable crane (36.76%) and chainsaw–medium-size cable crane (27.94%) were selected as the most suitable timber extraction systems for the steep terrain study area, according to the model. They were followed by chainsaw–forest tractor (23.52%), chainsaw–agriculture tractor (10.29%), and chainsaw–sledge yarder (1.49%) [29]. A slightly more complex project was produced by Picchio et al. [28]. In this study, a GIS model was developed to classify two forest estates in Central Italy as accessible or inaccessible areas for extraction by tractor with a winch and/or lightweight cable yarder, which are the most common extraction systems used in that area. Then, a "Least Cost Path" analysis was performed to design new hypothetical skid trails that could make all ownerships surface accessible. Finally, the authors made a survey analysis to validate the developed model and found a strong correlation between the model validation and the actual accessibility in the forest areas.

In the above-mentioned works, the study area included entire forest estates, usually hundreds or thousands of hectares. The first attempt to use GIS in a more accurate analysis and planning of a forest road network on a relatively small area (ca. 20–60 ha), dimensions comparable to a single forest yard intervention, was carried out in Picchio et al. [11]. In this study, three different GIS models, developed in previous studies, for the identification of forest winch accessible areas, were applied and field-validated in two different study areas in Central Italy. All three models showed optimum results in the prevision of winching areas in both study areas.

The next step should be the development of correction factors to further increase model efficiency, and their integration with forest harvesting scheduling models, such as the one developed by Vopenka et al. [30], inserting all these systems within the forest management plan.

3.2. GNSS Instruments

The global navigation satellite system (GNSS) has become one of the most popular techniques for fast and accurate positioning in open spaces. This method has been used in many areas of mapping because of the low cost and simplicity of use, compared to the standard surveying technique [31].

Gerlach [32] defined the development of this system 30 years ago as the most important recent innovation in the field of remote sensing, replacing traditional (manual, analogic, etc.) surveying methods with GNSS survey methods. The availability to collect information on machine performance and function allow the collection of information such as distances traveled, machine status, and productivity of the machine at each location.

Regarding the contribution of GNSS to the forest utilization sector, it is possible to identify two different groups of scientific contributions: The first group includes articles that show GNSS applications for the improvement of various forest utilization techniques; the second one is composed of articles that analyze and/or try to improve GNSS position accuracy under forest canopy cover.

Regarding the first group of articles in the analyzed period (2013–2019), most scientific papers focused on the possibility of using GNSS in order to define machine work productivity. Though this, at first glance, could seem interesting only from an academic point of view, it is actually an essential evaluation for technical-practical aims. In fact, all economic and logistic evaluation in forest yards, for example stumpage value evaluation, is strongly linked to work productivity.

GNSS devices allow a very interesting possibility to monitor operational time in forest logging operations with high level of mechanization (processor, cable crane, and wheeled skidder), with an error of working time evaluation ranging from 2.75% to 7% in comparison to the considerably more complex and costly chronometric field relieves [33–36].

Moreover, GNSS devices also showed feasibility for helicopter logging productivity analysis [37]. GNSS technology could be also used to evaluate forest utilization impacts, considering that reducing soil and topsoil impacts, linked with forest operations, is a central and essential aim of sustainable forest management research [38]. In fact, Veal et al. [39] studied the accuracy of this application to define areas where repeated traffic could lead to an excessive soil compaction or other undesirable impacts on the local environment.

Ellis et al. [40] showed the importance of GNSS technology in the evaluation of soil impact, claiming that such devices are currently more precise than UAV-LiDAR in detecting skid trails network linked to forest utilization.

According to the above, equipping all forest machines, and not only the newest ones, with GNSS devices, and sharing the recorded position with the control Institutions personnel, could be a powerful instrument for forest operations supervision, as it allows remote control of machines [33].

Together with GNSS, modern harvesters are equipped with computers able to collect and store a great deal of data on stem measurements, harvesting production, and machine parameters. These data are automatically collected by the measurement system unit at the harvesting head, linked to the OBC systems of the machine [41]. The information is recorded using a de facto standard called StanForD (standard for forest data and communication), which is used by all major manufacturers of cut-to-length (CTL) machines across the world [42,43]. There is a number of standard files produced when operating with StanForD, including: Apt (cross-cutting instructions), prd (production files), pri (production individual files), drf (operational monitoring data), and stm (individual stem data) [44]. Apt files are produced by the user, whereas the others are produced by the machine computer. These files can be used by forestry companies and contractors to manage production aspects [45]. Although StanForD files contain useful data, the process of extracting, storing, and analyzing them is complex. Software, for example SilviA, is used by both John Deere and Waratah to make StanForD files easier to be read, created, and edited. Advanced software, such as Timber Office from John Deere and Ponsse Opti from Ponsse, can be used to manage operations and for fleet control [46]. Moreover, several harvester control systems have a navigation system capable of displaying a range of base layer maps, which can include raster and vector data, such as digital elevation models (raster feature), stand maps (polygon feature), and power lines (line feature). The operator can navigate with a map displaying stand boundaries as well as restricted or dangerous areas based on the outputs presented on the machine's computer screen. Additional functions such as recording points (e.g., features of interest) and calculating areas are available in some systems. An example of GIS data development of StanForD data from a forwarder OBC system is presented in Figure 3.

Integrating GNSS and StanForD data could lead to various important and interesting forestry applications such as: Developing forest yield maps, useful for harvesting and management planning or evaluating work productivity to other parameters, for example stem diameter at breast eight (DBH), species, shift (day/ night), slope, and operator [46].

The last application of GNSS technology analyzed by scientific research in the last years, with regard to the above cited first group of articles, is GNSS application for workers' safety.

This is a key factor in sustainable forest management, especially considering that logging consistently ranks among the most dangerous occupations [47,48]. With a rate of 136 fatal injuries per 100,000 workers (91 fatalities total) in 2016, logging workers had by far the highest fatal injury rate in the United States [49]. Location-sharing devices, like global navigation satellite system–radio frequency (GNSS-RF) technologies, which share geographic coordinates, and radio-frequency identification (RFID) transmitters, capable of local relative positioning of worker proximity to equipment, have potential to increase workers' safety on logging operations [50].

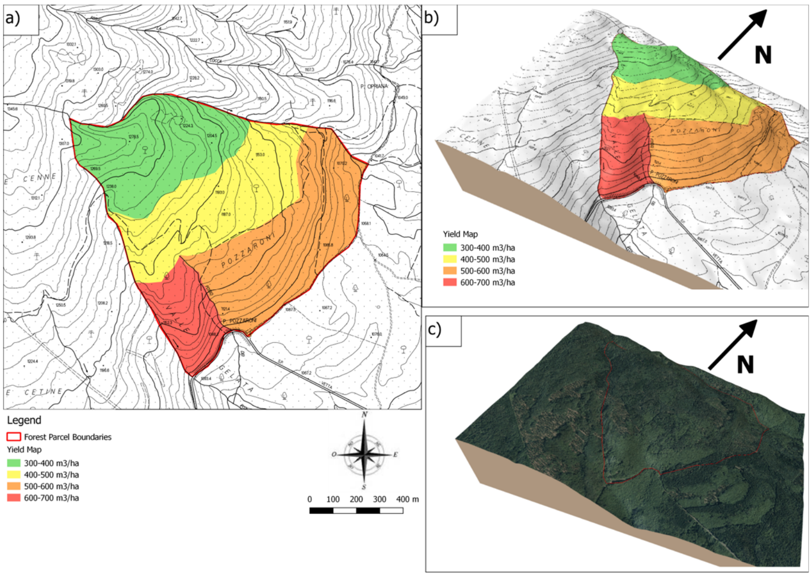

Figure 3. (**a**) Forest yield map developed from GIS elaboration of data from forwarder on-board computer (OBC) system (John Deere TimberLink). (**b**) The same forest yield map reported on a 3D model of the surface with the identification of contour lines. (**c**) 3D model of the surface with Orthophoto of the area.

GNSS-RF devices that facilitate location sharing in off-the-grid areas without cellular service include receivers that could synchronize with mobile phones or tablets by using Bluetooth and transmit GNSS locations throughout local networks, as well as dedicated radios with GNSS capabilities. These latter devices were originally developed for military applications, but in recent years, they have been increasingly considered for worker safety uses in natural environments [50].

Location sharing technology could increase team safety during logging operations and facilitate both injury prevention and response. For instance, location sharing devices with help alerts could allow isolated individuals to notify the coworkers or off-site response services of any emergency. In cases of incapacitation, automatic position updates may help coworkers if an individual requires aid. In both cases, geographic coordinates are shared to assist response efforts [51].

Considering the consistent importance of this technology's implementation in forest yards, many authors have addressed this issue.

Keefe et al. proposed the development of a system that allows operators to see the location of ground workers and other equipment on a digital display in real time, using location-sharing devices [52].

This system may increase workers' safety during logging, thereby reducing the incidence of fatal and near-fatal injuries [50]. Another scientific work developed a system in which virtual geofences encompassing high-risk areas during logging operations can be monitored by a mechanism to detect and alert operators of the presence of ground workers in hazardous areas [53,54]. Zimbelmann et al. expanded this concept to include the detection of workers and equipment in motion through real-time proximity analysis [55].

However, to improve the potential of this technology and guarantee workers' safety, it is fundamental to enhance positioning accuracy [56].

From this point, it is possible to explore the second group of scientific works, i.e., papers that analyze and try to improve GNSS positioning accuracy under forest canopy cover; this is a topic in which scientific research has been highly active in recent years [3,57–67].

First of all, it is important to provide a brief introduction on the problem.

GNSS technology works well in unobstructed open spaces and all GNSS manufacturers provide the accuracy of their receivers assuming them to work without any obstacles [63].

The fact that forest canopy cover may suppress the satellite signal is not taken into account [68]. Many factors linked with forest conditions can influence positioning accuracy. Forest canopy is a barrier for signal propagation, so the final radio wave is weak, and the reflection causes an elevated signal-to-noise ratio, which is called multipath effect [69–71]. The base idea of multipath is strictly connected to signal reflections from objects located near the receiver, which finally causes an error in distance measurements. There are many software and hardware solutions to weaken this effect, however the strong forest influence is not completely solved yet [72]. Moreover, the multipath effect is strengthened by high moisture conditions and by the presence of leaves [72,73].

Considering the above, today the position of one object (a machine or an operator) under forest canopy cover can be detected by GNSS technologies with an accuracy of 2–7 m with an average of 3 m and a maximum of about 20 m [3,74].

That being the case, enhancing GNSS positioning accuracy is a primary goal and it could be reached by integrating GNSS with other technologies like RTK, RBN DGPS [74], IMU sensors [3], or RF [75]. Using RTK, it is possible to reach centimeter-level accuracy [76]. Moreover, it is possible to have a positioning error below 1 m in forest conditions also by using RBN DGPS [74].

Kaartinen et al. [3] integrated a GNSS receiver with an IMU sensor to test the positioning accuracy compared to simple GNSS technology and it was found that GNSS-IMU reached an error of 0.7 m while the mean error of simple GNSS technology was between 4 and 9 m. An overall summary of various technologies of positioning correction is given in Table 1.

Table 1. Principal global navigation satellite system (GNSS) correction technologies and average positioning error from literature.

Technology	Average Positioning Error [m]	Reference
Simple GNSS receiver	4–9 m	[3]
RTK-GNSS	≅10 cm	[76]
RBN-DGPS	<1 m	[74]
GNSS-IMUs	0.7 m	[3]

To summarize, with current GPS-GNSS differential postprocessing technology, or by integrating GNSS with IMU sensors, it is possible to reach a positioning precision with an error below 1 m. Up to now, many precision forestry applications have been allowed, but still without the possibility of a complete machine automation.

3.3. Machine Sensors

Another important application in forest operation improvement is the integration, within forest machines like harvesters or forwarders, of different kinds of sensors able to detect particular parameters, which could be important to support forest utilization in various ways. As reported by Borz [77] in 2016, equipping forestry machines with a sensor system is very important to improve forest operations, and this should be done not only for CTL machinery, but these sensors should be also implemented on winch-assisted machineries like winch skidders. Very few papers have, in fact, analyzed sensors' usage in winch-assisted vehicles.

Analyzing recent scientific papers on the matter, the most investigated usage of sensors in the forestry sector has been dedicated to work productivity evaluation, which, as written in the above paragraphs of this review, is a very important parameter for multiple purposes.

The first kind of sensor used for this application has been the machinery vibration sensor, which has been demonstrated to be very useful in machine productivity analysis, with particular reference to delay time identification, quantification, and explanation [78,79]. In particular [79], a mean difference between the cycle times was obtained of an estimated <1 s.

Other studies have instead employed machine monitoring systems and OBC to evaluate work productivity. Manner et al. [80] used the John Deere Timber Link to evaluate forwarding productivity and Brewer et al. [81] adopted StanForD through Ponsse Opti2 information system. Both studies reached good performances in work productivity evaluation.

Again, with regards to productivity analysis, multi-camera security systems showed the possibility of analyzing the work cycles of a John Deere 540G cable skidder [82].

Concerning the implementation of various kinds of sensors on forestry machines, an interesting publication is Ding et al. [83], who described a novel stumpage detection method for forest harvesting, based on a 2D laser scanner and infrared thermal imager. According to this method, the stumpage information is captured by the two sensors and fused via image fusion and laser matching. Then, stumpage features can be extracted from the fused information. Next, an SVM (support vector machine) classifier model is constructed by sample training, according to the feature data. Finally, in contrast to SVM with default parameters, three different optimization algorithms were proposed to optimize SVM parameters. The results showed that this method could reach a detection rate of 96.7%. Ultrasonic sensors could instead be used for measurement of ruts depth in forwarding operation focusing on environmental impact characterization; according to the study results, ultrasonic sensors provide sufficient accuracy to characterize depth of ruts in 1.5 m long segments of strip-roads, including dynamic data on depth and length of ruts after each pass [84]. Using several different tools mounted on forestry machines, Marinello et al. [85] highlighted a clear relationship between roughness parameters and the vibration intensities in order to monitor and study the effects of different road surfaces on vehicle stability.

With regard to the economic function of forests, a very interesting work is Sandak et al. [86]. In this study, a sensorized processor was developed featuring the following sensors: Near infrared (NIR) spectrometer and hyperspectral cameras to identify surface defects, stress wave and time of flight sensors to estimate timber density, hydraulic flow sensor to estimate cross-cutting resistance, and delimbing sensors to estimate branches number and approximate position. Moreover, the processor prototype also deployed an RFID UHF system, which allowed the identification of the incoming tree and marked each log individually, relating the quality parameters recorded to the physical item and tracing it along the supply chain [86].

What this sensorized processor makes possible is an evaluation of timber quality and, linking with StanForD data and a machine monitoring system like Timber Link, a complete evaluation of stumpage value.

Another application of electronic sensors in forest operation is positioning sensors. Correct positioning of a harvester head—the part in which knowing the position is essential for cutting operation automation—is currently limited by two problems: The above-cited GNSS positioning error and the position of GNSS receiver, which is not located on the processor head but somewhere within the cabin. Starting from these claims, Lindroos et al. [87] analyzed various positioning methods i.e., angle/range sensors, tilt sensors, joint sensors, and IMU sensors. Angle and range-based methods derive the position by estimating the angles and/or distances between a given number of sensors and the harvester head. Joint estimating methods calculate the position based on the geometry of the crane combined with direct measurements of joint angles and displacements. Tilt sensors estimate the static position by sensing the head's orientation with respect to the earth's gravitational field. Finally, IMU sensors use a combination of accelerometers, gyroscopes, and magnetometers [87]. The authors' analysis highlights the joint sensors and IMUs as the methods with the greatest potential for implementation thanks to their accuracy, cost-effectiveness, and solidity [87].

Some kinds of sensors are, of course, also usable to pursue one of the most important aims of sustainable forest management, i.e., forest workers' safety. One application is on-field continuous measuring of cable tensile force during winching operation, which can be performed by cable tensile force measurement device like Cable-Bull® SR22/800 XR sensor (manufactured by the Honigmann Industrielle Elektronik GmbH) [88–90]. A summarizing view of the contribution of various sensors and electronic devices to SFM is provided in Table 2.

Table 2. Main sensors or electronic systems used if forest operations and their contribution to sustainable forest management (SFM).

			Sustainable Forest Management Contribution		
Sensor or Electronic System	**Uses**	**Reference**	**Economic Pillar**	**Environmental Pillar**	**Social Pillar**
Machine Vibration Sensors	Identification of delay time in work productivity analysis	[78,79]	✓		
Machine Monitoring Systems and OBC	Detailed work productivity analysis	[80,81]	✓		
Multi-Camera Security System	Work cycles analysis	[82]	✓		✓
2D Laser Scanner and Infrared Thermal Imager	Stumpage detection	[83]	✓	✓	✓
Ultrasonic sensors	Measurement of ruts depth	[84]		✓	
Kinect Depth Camera	Determination of forest roads' roughness	[85]	✓		✓
NIR sensor, Spectrometer and Hyperspectral cameras	Identify wood surface defects	[86]	✓		✓
Stress Wave and Time of Flight Sensors	Estimate timber density	[86]	✓		
Hydraulic Flow Sensor	Estimate cross-cutting resistance	[86]	✓		✓
Delimbing Sensors	Estimate branches number and approximate position	[86]	✓		✓
Joint sensors	Positioning of boom-tip	[87]	✓		✓
IMU sensors	Positioning of boom-tip	[87]	✓		✓
Cable tensile force measurement sensors	Measuring of cable tensile force during winching	[88,89]			✓

An Overview of Forest Machine Automation Purpose

In machinery, robotics, and engineering, the degree to which a specific task of a given machine is automated is known as the level of automation (LOA).

In the forest utilization world, the most advanced technology machines are harvesters and, secondly, forwarders. Nevertheless, these require almost complete operator input and so even mechanized harvesting or forwarding extraction method could be considered to have a LOA 0 [90].

LOA 1 products, such as computer-assistance for motion control, entered the market only a few years ago [91]. In particular, there are cranes equipped with motion sensors [92], computer support to the boom-tip [93], reduced crane vibration systems [93], active suspension [94], and hydraulic valves equipped with software control [95,96].

Future challenges are reaching LOA 2 and LOA 3, which respectively consist of an operator who choose an operating action according to the machine suggestion and in tele-operated or unmanned forest vehicles [91,97–99].

To summarize, forest engineers using GIS are currently able to analyze a forest parcel, assessing the best extraction systems and automatically tracing new skid trails network to optimize bunching-extraction with minimal costs, minimum environmental impacts, and maximizing workers' safety. GIS-created files can be integrated in harvesters' and forwarders' OBCs in order to display on the screen an optimal skid trails network and the geofences of restricted-access areas. GNSS technology could allow one to position a forest operating machine with a precision of about 3 m that could decrease at values lower than 1 m by integrating GNSS with other technologies such as RF or IMUs or adopting differential correction. Harvesters and forwarders are equipped, or could be, with various sensors which allow one to identify the position of trees to be harvested; have a better knowledge of the processor head position; and perform an on-field evaluation of work productivity, utilization costs, timber quality analysis, and wood tracing.

Considering the actual technologies, the above is the best possible and obtainable result. To reach the subsequent step, consisting of tele-operated or unmanned forest vehicles, the integration on forest machines of simultaneous localization and mapping (SLAM) algorithms seems to be needed [100].

3.4. A Little Focus on Smartphones Applications

Current generation Smartphones are able to act as GPS receivers [101] and to run software to process geospatial information. Kennedy et al. [102] examined the potential use of low-cost consumer-grade smartphone technology to perform and improve field data collection, in support of small- and medium-scale forest and management. Smartphones greatly increased workflow efficiency by reducing data transfer and processing times and eliminated the need to carry a separate global positioning system (GPS) device, map, paper forms, and digital camera. The GPS accuracy of smartphones was adequate enough to meet operational requirements (i.e., about 9 m) and provided the capacity to map forest features.

Recently, Costa et al. [103] tested a smart, cost-effective, mobile stereovision system for in-field estimation of dendrometry parameters (i.e., heights and diameters). The use of smartphones already allowed the introduction of the use of blockchain technology for the electronic traceability of wood from standing tree to final user. In fact, Figorilli et al. [104] developed the implementation of a blockchain architecture within the wood chain using an info tracing system based on RFID open-source technology, underlining the difference with the traditional documental/mechanical methods. This solution generated a real-time traceability solution for the entire wood supply chain and as atypical electronic technology, RFID identification can reduce some of the information gaps, especially in logistics, enabling real-time visibility into supply chains.

In synthesis, smartphone technology is able to act as a low-cost GPS receiver even if under forest canopy cover, with sufficient precision forestry usages. It can be very helpful to forest workers, for example, in displaying the geofences of the intervention area on the smartphone screen, allowing one to avoid trespassing the parcel boundaries or excluding restricted-access areas such as biodiversity hotspots. Moreover, the smartphone's positioning system is enough to allow the forest owner or the head of the forest firm to know the location of workers, and this is pivotal for what concerns workers' safety.

4. Conclusions

Electronic contribution to forest operation in the last years has been considerable and with the development of various modern information technologies, the forest sector has entered the electronic age. Various technological systems-instruments (GIS, GNSS, sensors, etc.) are advantageous in implementing forest utilization that incorporates all three pillars of sustainable forest management (economic, environmental, and social). The technical evolution started during this new century can only develop through a correct integration between mechanical developments and applications of electronic systems. While the development and interaction of these technologies are consequential steps between them, the use of these new applications on the other side, identified by many as Industry 4.0, represent the natural evolution that will lead this new century to complete diffusion of mechatronic systems. The integration of these systems could provide crucial results in improving forest operations and the application of advanced technologies and a variety of harvesting and monitoring techniques could be effectively combined together and applied in forest operation in order to meet forest worker safety, support environmental equilibrium, and guarantee high levels of productivity. The future challenges are linked with the possibility of enhancing automation level of forest machines in order to reach tele-operated or unmanned vehicles. At the small- and medium-scale forestry level, the possibility of using cost-effective technologies such as smartphones in forest operation is a key factor to give a new impetus to this sector, which has potential to counteract the abandonment of rural territories, and this is paramount, especially in the Mediterranean region.

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Acronyms and Forestry Technicality Used in the Text

ATV	All-terrain vehicle
CTL (cut to length)	Harvesting systems in which trees are delimbed and bucked into sorted piles at the stump prior to subsequent transport to the landing by skidding or forwarding
DGPS-DGNSS	Differential positioning system (DGPS-DGNSS) is a method of correction requiring at least two GPS-GNSS receivers; one placed at the base station whose geographic coordinates are precisely known and another placed in the field. Correction values from the base station can then be used to improve the positioning of the second receiver.
DSS (decision support system)	An information system that supports business or organizational decision-making activities and helps people to make decisions about problems.
GIS (geographic information system)	A system designed to capture, store, manipulate, analyze, manage, and present spatial or geographic data. GIS applications are tools that allow users to create interactive queries (user-created searches), analyze spatial information, edit data in maps, and present the results of all these operations.
GNSS (global navigation satellite system)	A satellite navigation system with global coverage, integrating both United States' global positioning system (GPS) and Russia's GLONASS.
GNSS-RF	System that integrates both GNSS and Radio Frequency.
ICT (information and communication technology)	An extensional term for information technology (IT) that stresses the role of unified communications and the integration of telecommunications (telephone lines and wireless signals) and computers, as well as necessary enterprise software, middleware, storage, and audiovisual systems, that enable users to access, store, transmit, and manipulate information.

IMU (inertial measurement unit)	An electronic device that measures and reports a body's specific force, angular rate, and sometimes the orientation of the body, using a combination of accelerometers, gyroscopes, and sometimes magnetometers. IMUs are typically used to maneuver aircraft (an attitude and heading reference system), including unmanned aerial vehicles (UAVs). Recent developments allowed production of IMU-enabled GPS devices. An IMU allows a GPS receiver to work when GPS-signals are unavailable, such as in tunnels, inside buildings, or when electronic interference is present.
LiDAR (light imaging, detection, and ranging)	A surveying method that measures distance to a target by illuminating the target with laser light and measuring the reflected light with a sensor. Differences in laser return times and wavelengths can then be used to make digital 3-D representations of the target.
LOA	Level of automation.
MCDA (multi criteria decision analysis)	A sub-discipline of operations research that explicitly evaluates multiple conflicting criteria in decision making.
OBC	On-board computers.
RFID (radio frequency identification)	System using electromagnetic fields to automatically identify, and track tags attached to objects.
RDN DGPS	Radio beacon differential global positioning system is a supplementary correction signal used by GPS receivers to increase the accuracy of GPS based positioning.
RTK (real time kinematic)	Real-time kinematic (RTK) positioning is a satellite navigation technique used to enhance the precision of position data derived from satellite-based positioning systems. It uses measurements of the phase of signal's carrier wave in addition to the information content of the signal and relies on a single reference station or interpolated virtual station to provide real-time corrections, observing up to centimeter-level accuracy. With reference to GPS in particular, the system is commonly referred to a carrier-phase enhancement, or CPGPS.
SLAM (simultaneous localization and mapping)	A process for which a robot moves in unknown environment, creates a map of this one, and is able to locate itself within this map.
SKID ROAD	a properly road, with all related infrastructures like drainage ditches, used by skidders or forestry fitted farm tractors for bunching and extraction of wood material.
SKID TRAIL	A trail with no infrastructures like drainage ditches, and so not a properly road, used by skidders or forestry fitted farm tractors for bunching and extraction of wood material.
SSF (small-scale forestry)	Forestry linked to small or family enterprises characterized by low-medium level of mechanization and poor amount of harvested timber volume.

StanForD (standard for forest data and communication)	Standard for communication between computers in forest machines.
STRIP ROAD	The same as skid trails but with particular reference to CTL machinery like forwarders and harvesters.
SVM (support vector machine) model	In machine learning, support-vector machines are supervised learning models with associated learning algorithms that analyze data used for classification and regression analysis.
UAV	Unmanned aerial vehicle.
VHF (very high frequency)	The range of radio frequency electromagnetic waves (radio waves) from 30 to 300 megahertz (MHz), with corresponding wavelengths of ten meters to one meter.

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