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New tree monitoring systems: from Industry 4.0 to Nature 4.0

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Abstract - Recently, Internet of Things (IoT) technologies have grown rapidly and represent now a unique opportunity to improve our environmental monitoring capabilities at extremely low costs. IoT is a new system of thinking in which objects, animals or people are equipped with unique identifiers and transfer data to a network without requiring human-to-human or human-to-computer interaction. IoT has evolved from the convergence of wireless technologies, microelectromechanical systems (MEMS) and the Internet. The development of these technologies in environmental monitoring domains allows real-time data transmission and numerous low-cost monitoring points. We have designed a new device, the TreeTalker©, which is capable of measuring water transport in trees, diametrical growth, spectral characteristics of leaves and microclimatic parameters and transmit data in semi-real time. Here we introduce the device's features, provide an example of monitored data from a field test site and discuss the application of this new technology to tree monitoring in various contexts, from forest to urban green infrastructures management and ecological research.

Keywords - Internet of Things; tree monitoring; ecophysiology.

Introduction

In recent years, a new trend in manufacturing technologies, generally referred to as Industry 4.0, has emerged, allowing to achieve a higher level of operational efficiency and productivity through automated and interconnected systems (Roblek et al. 2016). This was due to the combination of the technological concepts of cyber-physical systems and Internet of Things (IoT), a new paradigm according to which objects, but also living beings, can transfer univocally identified data to the internet without the interaction of humans (Misra et al. 2018). The IoT evolved from the convergence of wireless technologies, microelectromechanical systems (MEMS) and the Internet.

Industry 4.0 has indeed brought a major breakthrough in the field of industrial processes monitoring and it is therefore reckoned to represent a new stage, equivalent to a "Fourth Industrial Revolution", from which takes its name. The translation of such technologies into the field of environmental monitoring could bring the advantage of real-time data transmission from numerous measurement points at low cost, however, the applications to nature understanding and management are to date generally lacking.

Drawing inspiration from the concept of Industry 4.0, we, therefore, conceived the application of a system to the monitoring of physical and functional parameters of trees, in what can be defined as the Nature 4.0 approach. The implementation of such an observation system should be based on digital sensors featuring continuous operability and automatic data transmission in order to provide semi-real time monitoring of variables. Moreover it will represent both a decision support framework for environmental management – and a valid tool for scientific research in the field of trees ecology and ecophysiology (Bayne et al. 2017, Subashini et al. 2018).

The interest of managers of urban green infrastructures or forests would lie primarily in the constantly updated diagnosis of trees conditions relative to their vigour, growth rate and failure risk; spatially punctual and temporally dense data on the microclimate surrounding trees, their canopy spectral properties and functionality in terms of growth and water transport would provide researchers with insight on individual trees functional responses to their environment.

We developed a new multifunctional device, the "TreeTalker©", based on IoT systems, for the real-time observation of trees physical and biological parameters applicable to the monitoring of forests,

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agro-forestry systems and urban green infrastructures. This device is designed to be deployed on tree clusters and transmit data using technologies typical of the IoT systems, thus providing cost-effective, semi-real time data from the monitored targets. The use of TreeTalker devices can support informed decision making related to trees management in different spheres from urban settings to natural forests and it allows the monitoring of trees applied to forest research. In this paper, we describe the device, its measurement capabilities and the network architecture it makes use of. We also provide an example of preliminary results that have been collected at test sites where TreeTalkers have been deployed and discuss present and potential field of applications and device developments.

Materials and Methods

The TreeTalker (TT) consists of a microcontroller with an ATMega 328 processor chip enclosed in a case (11.5x6.5x6 cm) acquiring signals from a number of sensors designed for the measurement of variables including: water transport in the xylem of the trunk (sapflow), wood temperature and humidity, multispectral signature of light transmitted through the canopy, tree trunk radial growth, accelerations along a 3D coordinate system used to detect tree movements, air temperature and relative humidity which can be additionally complemented by soil temperature and volumetric water content (SWC).

A TT is typically mounted on trees by means of a belt tightened around the tree trunk, and powered by a combination of high-efficiency Lithium-ion batteries (3.7 V) and a small solar panel attached on the battery case (Fig. 1). Depending on enabled measurement types, acquisition frequency and installation location, the batteries autonomy is expected to span from 3 weeks to 1 year.

The sapflow density is retrieved according to the Heat Balance Method (Granier 1985) by monitoring the temperature of two 20 mm long probes inserted into the stem wood at 10 cm distance along the trunk vertical axis. The probe in the higher position is heated while the lower one provides the stem wood reference temperature and is additionally equipped with a capacitive sensor for wood moisture measurements. A similar technology is used in a dedicated probe for SWC and temperature measurements. Multispectral measurements of sunlight are performed across 12 bands covering the visible and near infra-red spectra and centred at the wavelengths of 450, 500, 550, 570, 600, 610, 650, 680, 730, 760, 810 and 860 nm (full-width half-max of 40nm) by means of a spectrometer with a field of view of 40° mounted on top of the TT case. Stem radial

Figure 1 - Tree-Talker installed for the monitoring of a tree and its power unit (battery case with photovoltaic panel).

growth is measured by an infra-red pulsed distance sensor positioned at few centimetres from the tree trunk's surface and kept in place by a carbon fibre stick anchored in the xylem. Any stem radial increment therefore translates into a reduction of the distance between the sensor and the targeted tree trunk's surface which according to laboratory tests can be determined with a resolution of not less than 100 µm for a sensor-target distance up to 5 cm. The TT incorporates an accelerometer providing data on changes of the device position over time and instant accelerations of the tree trunk where it is installed. This technology can be conveniently applied to monitor the root plate tilt with an accuracy of ± 0.01°, as well as the flection and the accelerations that tree trunks receive under the force of wind for the evaluation of tree failure risk. A thermo-hygrometer, embedded on the microcontroller, completes the set of sensors; air exchange through the device case is allowed by a 0.6 mm wide circular hole covered with a water vapor permeable membrane.

The TreeTalker features a wireless connection (using powerful low power chipset LoRa for data transmission) to a node managed by another microcontroller (TT-Cloud) serving up to 48 devices in one cluster (we suggest 20 to avoid data collision) and data transmission is typically set at hourly fre-

Table 1 - Components of the TT devices and their characteristics.

Device	Component	Description
TT (TreeTalker)	Sap flow	Reference and heated temperature probes (±0.1 °C). Thermistors manufacturer: Murata Electronics. Model: NCU18XH103F6SRB
	Stem humidity	Capacitive sensor MicroPCB (20x3x2) mm with copper plates.
	Canopy light transmission	Spectrometer-12 spectral bands (450, 500, 550, 570, 600, 610, 650, 680, 730, 760, 810, 860 nm) Full width half max: 20 nm (VIS);40 nm (NIR). Manufacturer: AMS. Model: AS7262 (Visible range), AS7263 (Near Infrared range)
	Tree trunk radial growth	Infra-red distance sensor (min ±100 µm) Manufacturer: SHARP. Model: GP2Y0A51SK0F
	Tree trunk axis movement	Accelerometer (± 0.01°) Manufacturer: NXP/Freescale. Model: Si7006
	Air temperature and humidity	Thermohygrometer (±0.1 °C ; ±2 %). Manufacturer: Silicon Labs. Model: MMA8451Q
	Flash memory for data storage	16Mbyte
	LoRa module for data transmission	Transmission 600 m (in urban/rural environment). It can reach >3 km in case line of sight
	4 Li-Ion batteries + solar panel	3.7 V
TT Cloud	Modem/router LoRa protocol	868 MHz with external antenna
	Modem GPRS	
	WiFi connection	alternative to GPRS if available
	Flash memory for data storage	16 Mbyte
	4 Li-Ion batteries +solar panel	3.7 V

quency although customizable. The TT-Cloud is in turn connected to the internet via the GPRS network and sends data to a computer server (Tab. 1).

To date, the performance of TreeTalkers is being tested at several sites, both in Italy and in Russia, with distinct characteristics in terms of climate, land cover/use, topography, exposure, tree species, age and stand density for the particular purposes of: (i) evaluating the reliability and operational limits of the sensors and of the data transmission system; (ii) estimate the battery autonomy and (iii) compile a list of recommendations for the set-up of the devices tailored to distinct installation environments.

One of the test sites is in the territory of the Moscow Timiryazev Agricultural Academy (MTAA; coordinates: 55°50' N; 37°33'E), chosen to deploy the devices in an urban setting exposed to continental climate with cold winters (Köppen climate classification Dfb). We installed TT devices on 13 street linden trees (*Tilia cordata* L.) in front of the MTAA premises in summer 2018. The installation height was at about 5 m, in order to prevent vandalism and the height of the trees reached up to 20 m. A second test site is in a mixed forest stand in the Umbria region in Italy (Piegaro forest, coordinates: 42°57'49"N 12°3'31"E, altitude: 430 m a.s.l) with a prevalent cov-

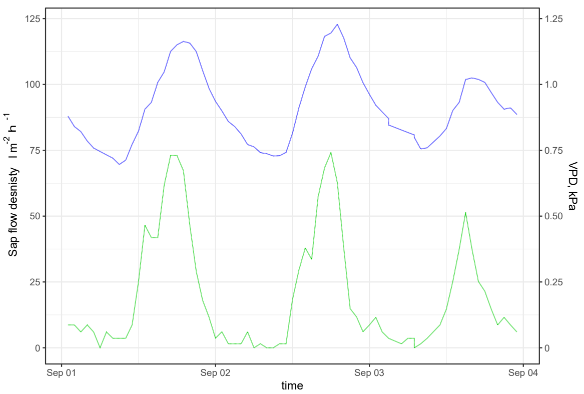

Figure 2 - Hourly data of sapflow density flux (green line) and vapor pressure deficit (VPD, blue line) measured over three days in early September 2018 at the MTAA test site. VPD was calculated from air temperature and relative humidity measured within the TT case.

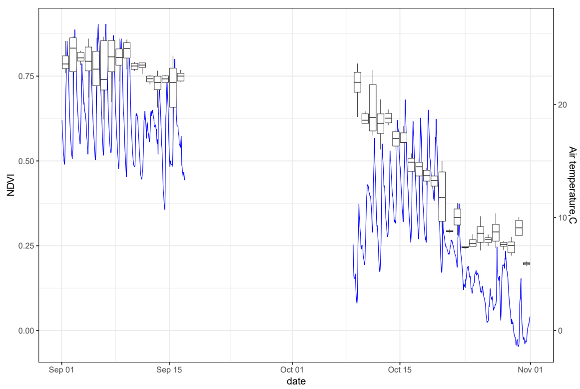

Figure 3 - Pattern of air temperature (blue line, hourly data) and NDVI (boxplots, daily data) measured between 1 September and 31 October 2018 capturing the progression of leaf senescence phase.

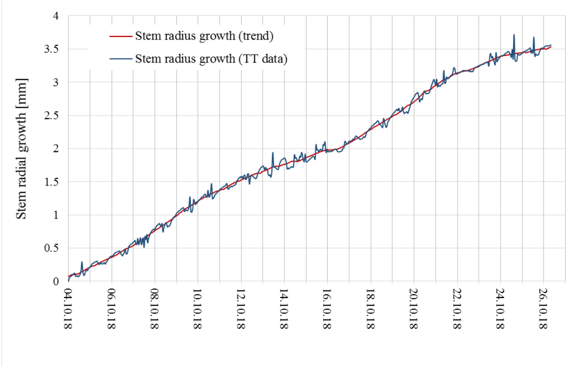

Figure 4 - Stem radial growth of a Douglas fir specimen at the Piegaro forest site inferred from variations of the sensor to tree trunk distance. Original hourly data (blue line) and moving average (n=24; red line) showing the trend of radial growth.

er of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), Scotch pine (*Pinus sylvestris* L.) and, to a very minor extent, of sessile oak (*Quercus petraea* (Mattuschka) Liebl.). A set of 13 Tree-Talkers was installed at the site in October 2018 and distributed according to the forest specific composition. The devices were positioned at about 1.5 m from the ground on trees having a stem circumference at breast height ranging between 93 and 227 cm (mean: 134.4 cm) and a mean canopy height of 18 m.

Results and Discussion

We provide some examples of data being collected in fall 2018 at the Moscow and Piegaro field test sites respectively in order to illustrate the capabilities of the measuring device in distinct fields of application. The first set of data was collected in the period September-October 2018 from a mature linden tree specimen with a breast height diameter of 39 cm. The characterization of the stem water transport variability, at hourly time step, in relation to the surrounding microclimate for a subset of 3 days is presented in Fig. 2 . Sapflow density flux, retrieved from the application of the Granier technique, featured maximum values between 50 and 75 l m^{-2} h^{-1}. The diel pattern and correlation of the sapflow density flux and the vapor pressure deficit (VPD) appears well evident (R=0.805; P<0.0001). The VPD, which combines the temperature and relative humidity signals measured by the integrated thermos-hygrometer of the Tree-Talker, represents the difference between the actual and saturation water vapor pressure in the air (Allen et al. 1998) and it acts as the main environmental driver of water transpiration.

A second example, concerning the monitoring of tree phenological dynamics (Fig. 3), illustrates the declining pattern of the transmitted Normalized Difference Vegetation Index (NDVI) during the phase of leaf senescence along with the decreasing trend of air temperature which is the main driver of leaf chlorophyll degradation (Soudani et al. 2012, Gill et al. 2015, Yang et al. 2017).

The monitoring of a Douglas fir tree (dbh: 60 cm; height: 18 m) at the Piegaro site provided a good example of the application of the Sharp sensor to the estimate of stem radial growth (Fig.4). The observations allowed the detection of variations in tree radius size in the order 0.1 mm at daily time scale, typically associated to the diel cycle of sapflow (Sevanto et al. 2008, Hermann et al. 2015). The radial growth trend, retrieved by filtering the data with 24 hour time window moving average resulted in 0.15 ± 0.08 mm d-1 (mean ± std.dev).

All data were acquired directly from a web server and no problems of data transmission with the LoRa protocol of radio communication between the TT devices and the TT-Cloud were encountered.

The use of IoT solutions with GPRS network to remote servers and online data processing is suggested in the field of trees monitoring. Detailed information at tree level can be potentially used for an accurate and temporally frequent assessment of the provided ecosystem services (e.g. climate regulation, water storage, carbon sequestration, pollutants removals, etc.) from the scale of tree to forest stand.

Continuous eco-physiological monitoring is crucial for understanding the biological response of trees to changes in the environmental condition, however it is generally not performed except for a limited number of instances limited to scientific research purposes. TTs allows the monitoring of trees in semi-real time and represent a valid tool to estimate to assess functionality and early detection of stress responses in trees (water stress, extreme temperatures, disease/pest attacks) which can be used for scientific research but also for decision making support in the management of forests, urban green infrastructures, agroforestry systems, orchards, etc. In the instance of an urban area, such data flow can lead to faster and better informed decisions to ensure a safe and healthy environment for citizens (Talavera et al. 2017).

Apart from the aspect of continuity, the TT device introduces innovative aspects to the traditional tree monitoring thanks to the technology of its sensors and their novel field of application. Continuous observation of tree canopy under a rich number of spectral bands (12) allows extracting information on changes of the colour of the leaves or defoliation which may be symptomatic of disrupted tree health. The TreeTalker allows also the monitoring of tree trunk diametrical growth with precision of high end dendrometers (Drewa and Downs 2009) and when installed at breast height (1.3 m), readings can be directly compared with traditional dendrometric data and used for the assessment of tree biomass and carbon stocks. The detection of a progressive inclination of trees or deviation from the normal response under wind load has a great potential of being applied in the context of an early warning system for hazard trees (James and Hallam 2013).

Conclusions

We presented a new device, the TreeTalker©, which is capable of measuring water transport in trees, trunk radial growth, spectral characteristics of the leaves, and microclimatic parameters.

The devices are typically installed in clusters of 20 units and at customizable time intervals transmit data via radio protocol to a receiving microcontroller which in turn sends them to a web server using the GPRS network. Near real time data from a continuous monitoring system are therefore available on the internet for visualization and further analysis.

Ongoing tests have so far demonstrated the capability of the device of successfully monitoring trees parameters and send data at hourly time step with an autonomy of not less than 3 weeks, also in the case high latitude autumnal conditions, as those encountered at the test site in Moscow city.

The application of Internet of Things technology, at the base of the TreeTalker, the monitoring of trees opens new opportunities in the field of forest and green urban infrastructures management as well as ecophysiological research.

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