Agrometeorological monitoring: Low-Cost and Open-Source – is it possible?
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Abstract: The paper describes the development and application of a low-cost and open-source system for agrometeorological monitoring. The system is based on the Arduino platform and agrometeorological sensors. Data are transmitted using a WiFi Shield and GSM/GPRS Shield. The system is equipped with different agrometeorological sensors: air temperature and relative humidity, solar radiation, wind speed, rain gauge, leaf wetness, atmospheric pressure, soil moisture, and a solar panel and battery made it energy self-sufficient. After a testing period in the lab, the field test was conducted in an experimental vineyard of CNR - IBIMET in the summer of 2013. The system has provided excellent results in terms of accuracy and stability of the acquired data from each sensor. This study shows that it is possible to monitor agricultural systems with low-cost devices. The potential of the system is high, as it has proved to be highly flexible to the different needs of the user due to the open-source philosophy, allowing maximum customization in terms of programming and the possibility of adding a wide range of sensors.

Keywords: Arduino, agrometeorological monitoring, precision farming, sensors, low-cost, open-source.

1. INTRODUCTION
Agricultural systems are in general highly heterogeneous, due either to intrinsic factors such as topography and soil characteristics or external factors such as cropping practices and seasonal weather trends. Precision farming was established with the aim of managing crop system variability in order to optimize agronomic practices, rationalize the use of inputs and maximize quality. Sustainable agriculture must be characterized by the following distinctive features: (i) reduction of environmental impacts, (ii) reduction of costs and (iii) maintenance of high quality yields. Among the challenges faced by decision-makers, an understanding of the crop nutritional deficit and water status plays a key role for variable rate fertilizer application and reduction of pesticides distribution. These traits could be monitored using tools that can describe the plant status and its environmental development in detail. The scenario is foreseen where the farm will become a multifunctional subject, productive but also environmentally sustainable.

Agricultural practices generate strong pressures on the environment, particularly with regard to changes in habitat, land and water use, and emissions of hazardous inputs (UNEP - International Resource Panel 2010). Indeed, 70% of freshwater withdrawals are used for agriculture; in the coming years we will face the challenge of producing more food with less use of water resources. In addition, according to the latest assessment by the Intergovernmental Panel on Climate Change (IPCC - Fifth Assessment Report - 2012), agriculture is responsible for over 13.5% of greenhouse gas emissions, a value higher than that reported for the transport sector (13%). Agriculture also contributes significantly with synthetic chemicals (pesticides). At the same time,
the agribusiness companies have to satisfy the needs of consumers, who are increasingly aware of food safety and quality standards. In this context, particular attention is placed on local products that characterize the “Made in Italy” agro-food, which is often associated with historical-cultural values related to production areas within a vision that combines food and territory. Taken together, these considerations highlight the need for a research effort and innovation to find solutions to limit and rationalize the use of resources and minimize the use of chemical fertilizers. To pursue these objectives, integrated tools have been developed for crop monitoring. Among the agrometeorological devices, the Wireless Sensor Networks (WSNs) are taking the spotlight. The WSNs are networks of sensors located within the crop systems that can measure, collect, process and share data in real time on the Web, making them immediately accessible to the end user. The spatial geometry of these networks is of great interest for applications in agriculture, by identifying conditions at different scales (Matese et al., 2014), which enable the different micro-areas to be pointed out within a cropping system. Indeed, many micrometeorological parameters play a crucial role on the plant health status and physiology. This new technological scenario allows the farmer to manage information and thus to know in real time the detailed conditions in the field, thanks to the combined use of cutting-edge sensors, instant data transmission and their accessibility on various devices. It becomes possible to program interventions such as irrigation or plant protection treatments, with advantages that are not only economic but also in terms of sustainability. The paradigm of “low-cost” and the integration of DSS (Decision Support System) data flows from WSN, will make it possible to directly implement intervention strategies/responses in the field.

Research in agrometeorology requires the monitoring of a large amount of data and a compromise usually has to be made between the type and amount of measurements required and the resources available for collecting. A large number of electronic solutions are available for automatic monitoring of experimental fields. Often monitoring systems contain proprietary technology that manufacturers do not wish to release, and are frequently designed to operate with only a particular manufacturer’s sensors. The users are locked into particular systems and technologies with steep costs for the various types of research they intend to undertake. In addition, scientific experiments require multiple sites and replicated treatments to satisfy observational and statistical requirements, and this can quickly become cost-prohibitive. The open source philosophy represents a breakthrough of considerable significance in the history of knowledge and scientific research. Open-source is based on an intellectual exchange and recognition of copyright in development mode, which is promptly reinvested to update and improve the project.

In recent years, the advent of low-cost microcontrollers has led to a rapid use in the scientific community (Vellidis et al., 2008; Fisher and Kebede, 2010). The possibilities afforded by an open-source hardware system, the most famous example being the Arduino project (Arduino, 2012), include the rapid prototyping of ICT systems where circuits models are licensed under Creative Commons and can be modified by the user. This leads to a coordinated development of the hardware and software with large network communities, which provide effective support. An advantage of open-source hardware is that a wide variety of ready-to-use – with few modifications – software is available for them on the Web, shortening development times. A wide range of low-cost interfaces, accessories and sensors are also available on the Internet, along with useful instructions.

The objective of this work was the development of two low-cost and open-source prototype agrometeorological stations for monitoring agrometeorological parameters.

2. MATERIALS AND METHODS

2.1. System description

The developed system (Fig. 1) is based on the Arduino platform equipped with an 8-bit programmable microcontroller ATmega328 (Atmel Corporation, San Jose,CA USA). The microcontroller contains 32 kilobytes (KB) of flash memory for program storage and 1 KB of non-volatile memory data storage. The I/O lines are made up of various digital and analog pins with 10-bit resolution. The device operates at 5V 16 MHz or 3.3V 8 MHz. The Arduino board is designed to allow for expansion through the connection of auxiliary boards or shields. The shields are connected through connecting pins that are arranged in the same physical configuration as the Arduino board. Programming libraries enable users to rapidly integrate new devices and sensors into projects without writing an extensive new program routine. The Seeeduino Stalker v2 is a hardware platform...
The system (Fig. 2) involved the use of two different data transmission modules, one based on GPRS communication using a Seedstudio GPRS Shield V2.0 modem and the other using a WiFi module (Seeedstudio WiFi Shield v1.1). With the GPRS modem, it is possible to use Arduino to dial a phone number or send a text message using AT commands. WiFi Shield uses a WiFi module RN171 to provide Arduino Ethernet standard functions. It is possible to easily connect the device to the wireless network 802.11b/g. With support for common TCP, UDP and FTP communication protocols, this WiFi Shield can meet the wireless network needs of most projects. It is also compatible with all types of Arduino, WiFi Shield uses a WiFi module RN171 to provide Arduino Ethernet standard functions. It is possible to easily connect the device to the wireless network 802.11b/g. With support for common TCP, UDP and FTP communication protocols, this WiFi Shield can meet the wireless network needs of most projects.

The software environment for programming with Arduino is available for download and installation in various computer operating systems (GNU / Linux, Mac OS X and Windows). Using the IDE, the user writes programs in a language based on C++. The IDE then compiles errors and downloads the compiled routine to the microcontroller. A terminal window is available for the text output from the Arduino board to the computer serial monitor. The contribution of the community is fundamental because, being an open-source project, it is possible to find many programming libraries that contain routines to simplify programming and incorporate advanced features, sample code and complete programs are available to download, use and modify, if necessary.
2.2. Sensor equipment

The devices allow the connection of a large number of sensors. The sensors operate at low voltages and output signals compatible with the microcontroller, including analog voltage, variable frequency and a selection of digital communication protocols. For this application, the following agrometeorological sensors have been used:

2.2.1. Air temperature and humidity
A DHT22 sensor (Sensirion AG, Switzerland) was integrated into the system for measuring the air temperature and relative humidity (Fig. 3). The sensor module, thanks to the very small dimensions of the CMOSens® technology, provides a digital signal for fully-calibrated relative humidity (±0.5%) and temperature (0.5 °C) allowing full integration into the system and excellent long-term stability. Further advantages are the very short response time of 4 seconds and the wide range of operating temperatures from -40 to 120 °C. The cost (10 Euros) as well as power consumption (up to 1μW) are minimal, this makes it a perfect sensor for low-cost and low-power applications.

2.2.2. Atmospheric pressure
Atmospheric pressure is measured by an MPL115A1 sensor (Freescale Semiconductor, Inc.). The digital barometric sensor uses MEMs technology to provide an accurate measurement within a range from 50kPa to 115kPa. The measurement accuracy, small size (5 x 3 x 1.2 mm) and minimum power consumption in operational (5μA) in sleep-mode (1μA), combined with low cost (about 10 Euros) make this product excellent for monitoring needs.

2.2.3. Solar radiation
The system is equipped with a sensor for incident solar radiation measurement. The technology is based on a photodiode contained in a Teflon structure to measure the diffuse component of the solar radiation (Fig. 4). Among the different models a silicon photodiode (Hamamatsu, S1226 -BK) was chosen in order to ensure a spectral response in the wavelength range 200 – 1000 nm. The sensor recognizes a specific wavelength of the electromagnetic wave incident and transforms this into an electric current signal by applying an appropriate electric potential to its ends. The advantage of this sensor over a photoresistor is the very high response speed, and it also provides a noise-free output signal with excellent linearity with respect to the incident light. This sensor perfectly fits the needs of the system due to the strength and longevity of the sensor, plus the fact that the operation of the photodiode does not require a power supply, but most especially because of a very good ratio between data quality and cost (5 Euros).

2.2.4. Leaf wetness
The Leaf Wetness Sensor detects the presence of surface moisture. This sensor works by having a series of exposed traces connected to the ground and the sensor traces are interlaced between the
grounded traces. The sensor traces have a weak pull-up resistor of 1MΩ. The resistor will pull the sensor trace value high until a drop of water shorts the sensor trace to the grounded trace. This circuit works with the analog pins of the board and detects the amount of water-induced contact between the grounded and sensor traces. The price is around 20 Euros.

2.2.5 Soil Moisture
Soil moisture has been monitored by equipping the system with a WaterScout SM100 sensor (Spectrum Technologies, Inc.). The sensor is based on the FDR (Frequency Domain Response) technique, which determines the volumetric percentage of water in the soil (WVC) measuring the change in the dielectric constant by means of a radio frequency electronic circuit. It presents excellent performance in terms of high-resolution (0.1%) and accuracy (3%) without the need for calibration. The price is around 100 Euros.

2.2.6 Soil temperature
Soil temperature is measured by a DS18B20 sensor (Maxim Integrated TM, California, USA). It is a waterproof digital probe, with the body covered with plastic film PVC insulation and the sensitive part in stainless steel, which makes it suitable for any gaseous, solid or liquid measuring environment. This sensor was chosen for its versatility and low cost (10 Euros). Furthermore, the sensitive metal part ensures a minimum inertia of the measure (response time < 750 ms), good precision (0.5 °C) and high resolution (from 9 to 12 bits).

2.2.7 Wind speed and Rain gauge
To measure the wind speed and precipitation a low-cost (76 Euros) Weather Sensor Assembly p/n 80422 by Argent Data Systems was used (Fig.5). The rain gauge is a self-emptying tipping bucket type. Each 0.011” (0.2794 mm) of rain causes one momentary contact closure that can be recorded with a digital counter or microcontroller interrupt input. The cup-type anemometer measures wind speed by closing a contact as a magnet moves past a switch. A wind speed of 1.492 MPH (2.4km/h) causes the switch to close once per second.

2.3 Power supply
The power supply consists of 12 V/ 4.5 Ah lead battery (Fig. 1) and a 50Wp solar panel (Fig. 5). A 5 V low-dropout DC/DC converter has been added to adjust the battery voltage (Fig. 1). The elements are contained in a watertight case with IP 67 protection.

3. RESULTS AND DISCUSSION
The agrometeorological application implemented two systems that differ by sensors equipment. The first system is a traditional agrometeorological...
station with the sensors described in materials and methods. The second system can be considered as a low-power node without rain gauge or anemometer that must be handled with interrupt requiring a fixed idle state of the board. The latter system was planned with a “sleep mode” routine in which consumption is considerably reduced, only a few mA on average. A comparison versus research grade agrometeorological stations could be reported considering Campbell Scientific and Davis weather stations as typical systems used for research purposes. A CR1000-based weather station, measuring standard meteorological sensors, and Vintage Pro 2 have an average current drain of 0.8 mA. The setup was very simple thanks to the “sandwich” implementation with several layers (shields). The libraries for the management of all sensors were easily found on the Web and then modified. The software consisted of a three layer script: (i) a root program with the library initialization and time-elapse for data acquisition, (ii) a second program with the sensor acquisition procedures and (iii) the third with the data transmission procedures by GSM/GPRS or via the WiFi module. With regard to the data format restitution, since these systems have been used mainly for research purposes, only string values were transmitted and stored. On the server side, we had a Linux CentOS 5 server running on a i686 machine, with a VSFTPD server set-up. Output data were stored with hourly frequency, and a simple control program was compiled to check dataset consistency, and notify the operator of any problem that might have arisen in the transmission chain. The firmware provided the data acquisition and transmission from the sensors every 15 minutes, once acquired from the remote server; the data were stored in “csv” format files. After a testing period in the lab, the field test was carried out in a CNR - IBIMET experimental vineyard (Sesto Fiorentino, Italy) in the summer of 2013. The system has provided excellent results in terms of accuracy and stability of the acquired data from each sensor. The power supply test in the laboratory allowed us to evaluate an efficiency of at least 10 days of energy independence in the absence of solar panel charging. This confirms the great potential of the system in terms of both low energy consumption and high operational efficiency. In detail, the experience gained from these tests has shown advantages and limitations in the use of open-source technologies and low-cost devices for agrometeorological applications:

As regards the advantages:
- The quality of the electronic components of these devices is already good and reliable for the purposes of agrometeorological monitoring;
- The prototype cost including devices and related Arduino shields, sensors, box and all components for power supply and installation is estimated at around 500 Euros. This allows for a dense monitoring useful
for many applications, where the data are usually taken from a small number of stations that are not representative of the experimental site;

- The Arduino community (http://forum.arduino.cc) shares all the libraries, programs and hardware scheme, so the user could easily find a solution to all kinds of issues on the GitHub database.
- The Arduino based technologies enable rapid prototyping and use of a wide range of sensors useful for all the different monitoring needs.

Concerning the limitations:
- The low-cost sensors quality does not conform to standards set by WMO (World Meteorological Organization), so a characterization and calibration study becomes necessary of each sensor’s responses with reference to WMO standards sensors. Figure 6a-b show the comparison results of low cost versus reference sensors equipment in laboratory. The low cost temperature and humidity sensor was compared with a Vaisala HMP45 humidity and temperature probe as reference (Fig 6a). Solar radiation sensor was compared with a Hukseflux SR11 pyranometer (Fig 6b);
- Traditional equipment have a much larger memory capacity for data-logging purpose compared to low cost devices.
- The hardware elements setup is still at the prototype stage, which presents problems in industrialization and large-scale production;
- Open-source community could suffer a negative effect due to the loss of control or standards;
- One of a limiting factors to the diffusion of open-source technology is that companies show lack of interest in a non-proprietary product, because it could be easily copied.
- The research experience in weather monitoring procedures problems plays a key role in driving technological innovation in an open-source and especially low-cost direction.

Many studies have presented monitoring solutions with the prerogatives of open-source and low-cost for different applications, for example the control of soil moisture and field irrigation (Fisher and Gould, 2012) or biomass evaluation using optical sensors for image acquisition (Kanda et. al., 2011). Others proposed wireless sensor applications in precision viticulture (Matese et al., 2013; Zachariadis and Kaskalis, 2012), which enable site-specific microclimate monitoring in vineyard. Sensor-web and GeoDB represent the potential of those technologies, and allow information integration and the creation of interfaces for easy access to smartphone applications (Apps). At the same time other solutions that supply an excellent DSS are:

data correlation with location-based information, Internet of Things (IoT) applications, models for the optimization of sustainability in agronomic interventions, implementation of an actuators-based system (e.g. management of automated irrigation) and data analysis providing semantic aggregation.

4. CONCLUSION

Technological progress has created a fertile substrate for a new phase of agricultural modernization, in terms of low-cost, adaptability and flexibility, making it more accessible for scientific purposes and operating innovative tools aimed at supporting decision-making. Although the system presented in this work is an early-stage prototype, the preliminary results have shown good performance in terms of autonomy and quality of data transmission, with features that meet any requirement of micrometeorological monitoring, such as power consumption...
and low cost. The potential of the system is high, as it has proved to be highly flexible to the different needs of the user due to the open-source philosophy, allowing maximum customization in terms of programming and the possibility of adding a wide range of sensors. Moreover, it suggests the need for every technological institute to provide an institutional “Github” where it shares all the codes developed for applications and not just publish scientific papers in which very often the “experiment repeatability” is, in our opinion, very ephemeral. Going back to the initial question: Agrometeorological monitoring: Low-Cost and Open-Source - is it possible? The answer we can give based on our experience is: WE CAN DO IT!

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REFERENCES