A Pattern for a UAV-aided Wireless Sensor Network

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Energy efficiency is a critical constraint in wireless sensor networks. Wireless sensor networks (WSNs) consist of a large number of battery-powered sensor nodes, connected to each other and equipped with low-power transmission radios. Usually, the sensor nodes closer to the sink are more likely to become overloaded and subject to draining their battery faster than the nodes farther away, creating a funneling effect. The use of a mobile device as a sink node to perform data gathering is a well known solution to balance the energy consumption in the entire network. To address this problem, we consider here the use of a UAV as a mobile sink. An unmanned aircraft vehicle (UAV) is an aircraft without a human pilot on-board, commonly known as Drone. A pattern for a UAV-aided Wireles Sensor Network simplifies the design and implementation of a network with such complexity and makes easy to integrate it with the remaining IT systems. This work presents an example of how this pattern can be applied to implement a mining dam monitoring system to warn and possibly avoid a deadly collapse.

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1. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of a large number of battery-powered sensor nodes, connected to each other and equipped with low-power transmission radios. WSNs have been used to monitor, detect, and track physical events. Usually these devices perform three main tasks: (i) sense the environment acquiring data from the surroundings, (ii) process and store the acquired data, and (iii) transmit by radio the acquired data to a data gathering point called sink node or base station [Akyildiz et al. 2002].

Most WSN architectures are based on the assumption that all nodes are connected to each other and that any two nodes could communicate directly or through multi-hop paths. This means that the sensor nodes are static and there is no mobility in neither the sensors nor the sink node. Adding a mobile device like an unmanned aircraft vehicle (UAV) to the infrastructure helps to improve reliability, connectivity, and energy efficiency [Anastasi et al. 2009; Kansal et al. 2004].

Recent developments in the microelectronics industry and the cost reduction in large-scale manufacturing have driven a popularization of UAVs. UAVs can be used not only as recreational objects, but also as a powerful

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technology for a large number of applications like monitoring (power lines, crops, structure and building health), event detection (flood, fire, storms, intrusions) and surveillance. The first UAV was used on August 22, 1849, when the Austrians attacked the city of Venice in Italy with unmanned balloons loaded with explosives [Cook 2007], but the use of sensors like gyroscopes and radio control techniques only started in the early 1900s, and was originally focused on military applications. The first large scale production took place only after World War II [Sullivan 2005].

In this paper we present a pattern that describes the use of the UAV as part of a WSN for data gathering. It complements our patterns for sensor networks [Cardei et al. 2011; Sahu et al. 2010] by concentrating in the data collection process. This work is organized as follows. In section 2, we present our UAV-aided wireless sensor network pattern and in section 3 we present our conclusions. Our audience includes designers of wireless networks as well as users and administrators of such networks.

2. UAV-AIDED WIRELESS SENSOR NETWORK

2.1 Intent

Wireless Sensor Networks (WSNs) can be used to monitor and gather data from remote and inaccessible areas. A UAV is used for data gathering, and can also be used to send control messages to the sensor nodes.

2.2 Example

Let us consider a country where a large number of people live downhill from dams built for mining companies with poor control and lack of regulations. In these cities, during the rainy season, dams may fail and a disaster may occur at any time, killing hundreds of people. For instance, Figure 1 shows the most recent deadly mining dam collapse that happened in Brazil on Jan, 25th of this year.

Fig. 1. Deadly mining dam collapse in Jan 2019 at Brumadinho, MG. Brazil [Times 2019]

Brazil counts 87 mining dams built with the method known as upstream tailings construction. This method of design is the same as the one that collapsed recently [Times 2019]. If not monitored carefully, a collapse could happen again any time with catastrophic consequences.

This system detection can also help to monitor the risk of collapse of the tailings dam built to dispose of iron ore waste. According to the Brazilian Mining Institute [Institute 2018], the country is the second largest producer of iron ore in the world after China.

2.3 Context

Wireless Sensor Networks (WSNs) have been used in many areas, especially for environmental monitoring. Sensors may be spread in a wide geographic area. There are many applications in which WSNs can be deployed to provide real-time data to help control and protect the local environment. For instance, we may need to monitor and manage the level of soil moisture to avoid landslides, the quality of the air, the weather in extreme situations like hurricanes, floodings and fire in remote areas, animal behavior, traffic conditions and even to monitor the enemy in military missions.

2.4 Problem

In many specific situations, human-only monitoring could not be enough nor efficient to avoid future problems or detect significant trends. Most of the deadly disasters presented previously happened due the lack of observation and/or lack of accurate information. Also, it could be too late to apply countermeasures if an important symptom is not detected in time. The necessity of monitoring large areas using accurate sensors and the necessity of improvements in data gathering lead us to define our problem as follows:

How can we monitor and gather data from large areas, and how we can deliver this information to a centralized Base Station in an efficient and timely manner?

Below we describe the forces that constraint a possible solution:

—**Efficient data gathering:** the data must be gathered and transmitted to the base station (BS) in an efficient manner, otherwise we might lose important data.

—**Timeliness:** the gathered information should be communicated to the BS within a predefined time; the information may not be useful if not delivered in time.

—The data gathering process must be **reliable**, otherwise some of the sensor data could be lost.

—**Security:** the gathered data should be transmitted in a secure way. This is especially important in hostile environments.

—**Power consumption:** the UAV should have enough battery power to allow it to cover the area of the complete network.

—**Reach:** We may want to cover WSNs spread in a very large area.

2.5 Solution

Add a UAV to the sensor network. The UAV can be fast and effective to collect information from sensors scattered in a large geographic area. Adding security and reliability patterns to the basic architecture can make it secure and reliable.

Figure 2 shows the UAV being used as a sink node to gather data in a wireless sensor network. The UAV moves, scans the network and collects the data transmitted by the nodes.

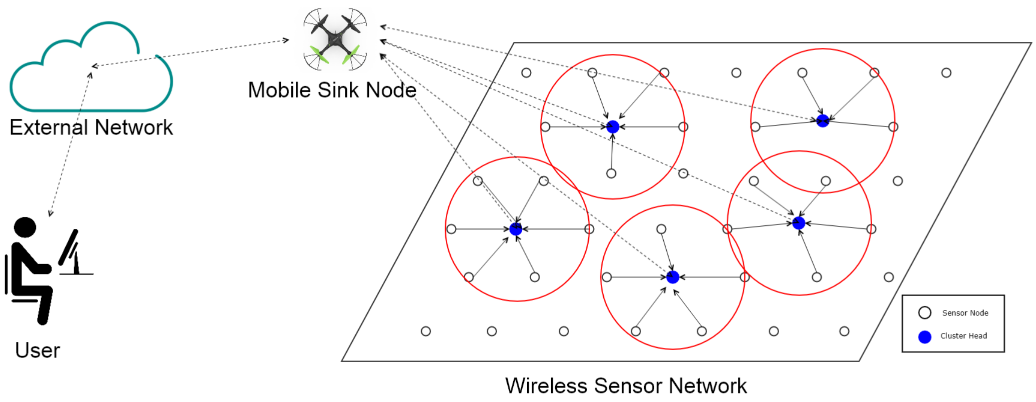

Fig. 2. UAV-aided Wireless Sensor Network

2.6 Structure

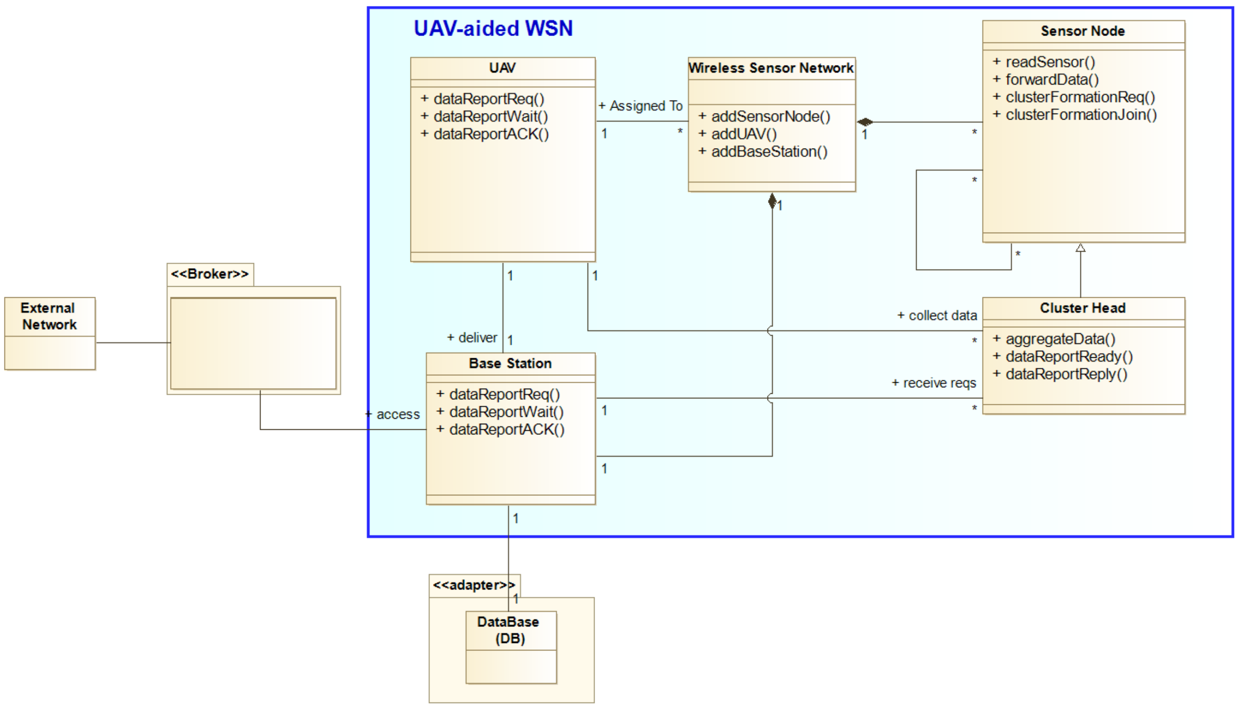

Fig. 3. Class Diagram of the UAV-aided Wireless Sensor Network

Figure 3 shows a class diagram of the UAV-aided WSN. The UAV acts as a mobile sink node and the network is composed of several Sensor Nodes sensing the environment and reporting data to the UAV. The sensor nodes can communicate with other sensor nodes and the UAV (if it is in range). The sensor nodes can organize themselves into clusters. Each cluster can have at maximum one Cluster Head (CH), that receives, stores and processes data from its nodes. The UAV collects data from Cluster Heads.

2.7 Dynamics

Figure 4 shows some of the use cases that describe the dynamics of the UAV-aided wireless sensor network architecture, which include Setup Nodes, Setup UAV, Deploy Nodes, Activate Nodes, Activate UAV, Collect Data, Aggregate Data, Deliver Information, and Deactivate UAV. We describe here the use cases, “Collect Data” and “Deliver Information”.

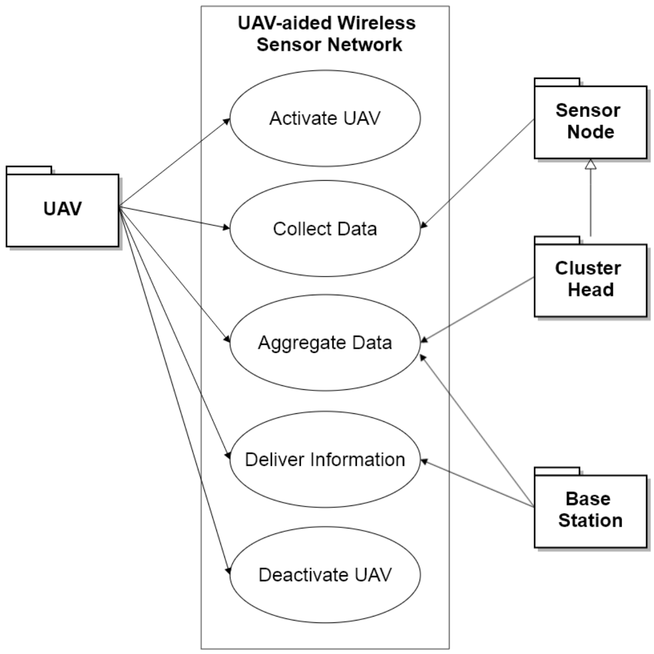

Fig. 4. The Use Case Solution Description

Use Case: Collect Data (Figure 5)

The UAV receives messages from the cluster heads in the WSN and starts the data gathering. When the UAV reaches the target point, it performs the data collection from that cluster head.

Precondition: Sensor nodes have been activated.

Description:

—The sensor nodes {sn_1, sn_2, sn_3, ... ,sn_n} read information from their sensors and forward the information to the ClusterHead1.
—The ClusterHead1 aggregates all received data from sensor nodes in a package.
—The ClusterHead1 reports to the UAV that the information is ready to be transmitted.
—The UAV replies back to ClusterHead1 informing it has to wait until it can perform the data gathering.
—The UAV starts the data gathering flying to the next cluster head.

—In range with the ClusterHead1, the UAV requests the data.
—The ClusterHead1 replies back with the information.
—The UAV acknowledges that the data was successfully received.

Post Condition: The data from a WSN has been collected.

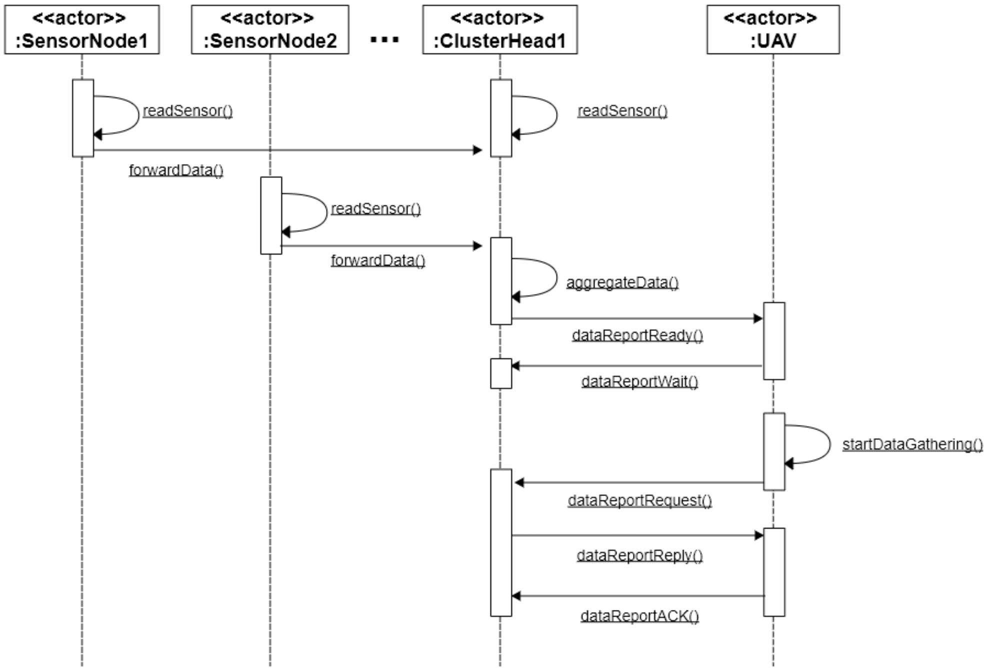

Fig. 5. Sequence Diagram of Use Case "Collect Data"

Use Case: Deliver Information (Figure 6)

Precondition: The data from all cluster heads have been collected and the UAV is in range of the BS

—The UAV reports to the Base Station that the information is ready to be transmitted.
—The Base Station requests the data.
—The UAV replies back with the information.
—The Base Station acknowledges that the data was successfully received.

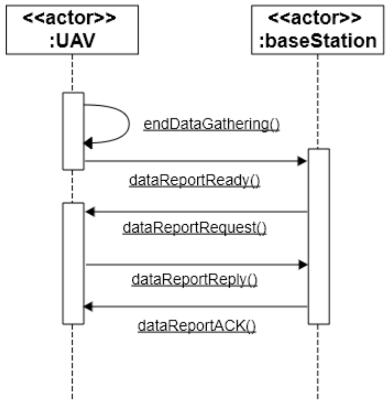

Fig. 6. Sequence Diagram of Use Case “Deliver Information”

2.8 Implementation

The user can buy commercially manufactured UAVs or it can be built using parts sold separately. The same happens to the sensor nodes, the user can buy or build according to the application. Both, the UAV and sensor nodes can be programmed to perform a pre-defined task and they start to work as soon as they are deployed. As mentioned before, both devices are equipped with wireless radio and can transmit their data directly to the user or using a network.

The steps to implement the solution are as follow:

—Define the area to be monitored.

—Define the position of the base station.

—Configure the UAV according to the application to receive messages and collect data at the cluster heads.

—Start the monitoring.

2.9 Example Resolved

A landslide detection system uses WSNs to detect the slight movements of soil and changes in various parameters that may occur before or during a landslide. Through the data gathered it might be possible to know the impending occurrence of landslides long before they actually happen, specially using the UAV to reach these remote access areas. The information triggers an alert in the neighborhood with the potential risk of landslide and/or collapse of the tailings dam. It is now possible to avoid deaths or accidents.

2.10 Known Uses

Landslide detection, water level monitoring, earthquake detection, dangerous gas leakage, forest fire detection, air pollution monitoring are examples of known uses of applications using UAV-aided Wireless Sensor Network to disaster management.

The authors in [Ramesh 2009] proposed the WINSOC (Wireless Sensor Network with SelfOrganization Capabilities for Critical and Emergency Applications) to predict the chance of occurrence of a landslide using WSNs to detect rainfalls. AWARE (Autonomous SelfDeploying and Operation of Wireless Sensor-actuator Networks Cooperating with Aerial Objects) [Ollero et al. 2007] is an European project that combines WSNs and UAVs to detect hazardous events like fire using temperature sensors. The application presented by [Cayirci and Coplu 2007] named SENDROM (Sensor Network for Disaster Relief Operations Management) uses WSNs to predict and manage earthquake disasters in Turkey. More specific approaches focusing in disaster applications can be found in Kaur et al. in [da Silva et al. 2010] and Chen et al. in [Chen et al. 2013].

2.11 Consequences

The UAV-aided Wireless Sensor Network Pattern has the following advantages:

—**Efficient data gathering:** the data collection capacity of UAVs makes this process very efficient. It can also collect data from a variety of sensors for different measures.

—**Timeliness:** the speed of a UAV assures timely delivery

—**Reliability:** If the UAV is well maintained, it is a reliable way to collect and deliver data. We can also have a backup UAV.

—**Security:** we can build a secure channel using cryptography, thus assuring the confidentiality of the data during transmission. The BS can have an authorization system to control access to specific measures.

—**Power consumption:** The UAV can be well maintained and its batteries replaced or charged frequently.

—**Reach:** With a UAV we can reach much farther distances than relying in the direct radio transmission from the sensors to the BS.

This pattern has the following liabilities:

—**UAV cost and maintenance:** The cost of UAVs is constantly decreasing so it is possible to find cost-effective solutions. The cost of maintenance is relatively small.

—**Complexity:** The system is now more complex and requires more specialized knowledge to manage.

2.12 Patterns Used in the Implementation

—Broker [Fernandez-Buglioni 2013]: users can access the collect data through the network with authorized access.

—Adapter [Gamma et al. 1995]: the base station stores the data received by the UAV in a database for future access and analysis.

2.13 Related Patterns

—Sensor Node: A pattern for a sensor node is presented in [Cardei et al. 2011]. It describes the structure of each network node.

—WSN: This pattern describes the structure and general architecture of a wireless sensor network [Sahu et al. 2010].

3. CONCLUSIONS

In wireless sensor networks, sensor nodes closer to the sink are more likely to become overloaded (by receiving a considerable amount of data packets) and subject to draining their battery faster than the nodes farther away, reducing the network lifetime. The UAV-aided Wireless Sensor Network pattern abstracts the architectural aspects of using a UAV as a mobile sink node in a wireless sensor network to avoid this problem. This setup can be applied to prevent deadly disasters in different situations like landslide detection, water level monitoring, earthquake detection, dangerous gas leakage, forest fire detection and air pollution monitoring. Other uses in a more general context can be found in [Rodrigues et al. 2017], including environmental monitoring, farm activities, and border surveillance.

REFERENCES

Ian Fuat Akyildiz, Weilian Su, Yogesh Sankarasubramaniam, and Erdal Cayirci. 2002. Wireless Sensor Networks: A Survey. *Comput. Netw.* 38, 4 (March 2002), 393–422. DOI:http://dx.doi.org/10.1016/S1389-1286(01)00302-4

Giuseppe Anastasi, Marco Conti, and Mario Di Francesco. 2009. Reliable and Energy-efficient Data Collection in Sparse Sensor Networks with Mobile Elements. *Perform. Eval.* 66, 12 (Dec. 2009), 791–810. DOI:http://dx.doi.org/10.1016/j.peva.2009.08.005

Mihaela Cardei, Eduardo B. Fernandez, Anupama Sahu, and Ionut Cardei. 2011. A Pattern for Sensor Network Architectures. In *Proceedings of the 2Nd Asian Conference on Pattern Languages of Programs (AsianPLoP '11)*. ACM, New York, NY, USA, Article 10, 8 pages. DOI:http://dx.doi.org/10.1145/2524629.2524641

Erdal Cayirci and Tolga Coplu. 2007. SENDROM: Sensor Networks for Disaster Relief Operations Management. *Wirel. Netw.* 13, 3 (June 2007), 409–423. DOI:http://dx.doi.org/10.1007/s11276-006-5684-5

Dan Chen, Zhixin Liu, Lizhe Wang, Minggang Dou, Jingying Chen, and Hui Li. 2013. Natural Disaster Monitoring with Wireless Sensor Networks: A Case Study of Data-intensive Applications Upon Low-Cost Scalable Systems. *Mob. Netw. Appl.* 18, 5 (Oct. 2013), 651–663. DOI:http://dx.doi.org/10.1007/s11036-013-0456-9

K. L. B. Cook. 2007. The Silent Force Multiplier: The History and Role of UAVs in Warfare. *2007 IEEE Aerospace Conference* (2007), 1–7.

Rone Ilidio da Silva, Virgil Del Duca Almeida, Andre Marques Poersch, and Jose Marcos Silva Nogueira. 2010. Wireless sensor network for disaster management. 2010 IEEE Network Operations and Management Symposium - NOMS 2010, Osaka, Japan, 870–873. DOI:http://dx.doi.org/10.1109/NOMS.2010.5488351

Eduardo Fernandez-Buglioni. 2013. *Security Patterns in Practice: Designing Secure Architectures Using Software Patterns* (1st ed.). Wiley Publishing.

Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides. 1995. *Design Patterns: Elements of Reusable Object-oriented Software*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA.

Brazilian Mining Institute. 2018. Informacoes e Analise da Economia Mineral Brasileira 7 edicao. (14 July 2018). http://www.ibram.org.br/sites/1300/1382/00004035.pdf

Aman Kansal, Arun A. Somasundara, David D. Jea, Mani B. Srivastava, and Deborah Estrin. 2004. Intelligent Fluid Infrastructure for Embedded Networks. In *Proceedings of the 2Nd International Conference on Mobile Systems, Applications, and Services (MobiSys '04)*. ACM, New York, NY, USA, 111–124. DOI:http://dx.doi.org/10.1145/990064.990080

A. Ollero, P. J. Marron, M. Bernard, J. Lepley, M. la Civita, E. de Andres, and L. van Hoesel. 2007. AWARE: Platform for Autonomous self-deploying and operation of Wireless sensor-actuator networks cooperating with unmanned AeRial vehiclEs. In *2007 IEEE International Workshop on Safety, Security and Rescue Robotics*. 1–6. DOI:http://dx.doi.org/10.1109/SSRR.2007.4381259

Maneesha V. Ramesh. 2009. Real-Time Wireless Sensor Network for Landslide Detection. In *Proceedings of the 2009 Third International Conference on Sensor Technologies and Applications (SENSORCOMM '09)*. IEEE Computer Society, Washington, DC, USA, 405–409. DOI:http://dx.doi.org/10.1109/SENSORCOMM.2009.67

M. Rodrigues, D. Pigatto, J. Fontes, A. Pinto, J. Diguet, and K. C. Branco. 2017. UAV Integration Into IoIT: Opportunities and Challenges. 6–7.

Anupama Sahu, Eduardo B. Fernandez, Mihaela Cardei, and Michael Vanhilst. 2010. A Pattern for a Sensor Node. In *Proceedings of the 17th Conference on Pattern Languages of Programs (PLOP '10)*. ACM, New York, NY, USA, Article 7, 7 pages. DOI:http://dx.doi.org/10.1145/2493288.2493295

J. M. Sullivan. 2005. Revolution or evolution? The rise of the UAVs. In *Proceedings. 2005 International Symposium on Technology and Society, 2005. Weapons and Wires: Prevention and Safety in a Time of Fear. ISTAS 2005.* 94–101. DOI:http://dx.doi.org/10.1109/ISTAS.2005.1452718

New York Times. 2019. Brumadinho Dam Collapse: A Tidal Wave of Mud. (14 July 2019). https://www.nytimes.com/interactive/2019/02/09/world/americas/brazil-dam-collapse.html