Design of Communication and Control for Swarms of Aquatic Surface Drones

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Keywords: Robotics Platform, Digital Manufacturing, Mesh Networks, Evolutionary Robotics, Decentralized Control

Abstract: The availability of relatively capable and inexpensive hardware components has made it feasible to consider large-scale systems of autonomous aquatic drones for maritime tasks. In this paper, we present the CORATAM and HANCAD projects, which focus on the fundamental challenges related to communication and control in swarms of aquatic drones. We argue for: (i) the adoption of a heterogeneous approach to communication in which a small subset of the drones have long-range communication capabilities while the majority carry only short-range communication hardware, and (ii) the use of decentralized control to facilitate inherent robustness and scalability. A heterogeneous communication system and decentralized control allow for the average drone to be kept relatively simple and therefore inexpensive. To assess the proposed methodology, we are currently building 25 prototype drones from off-the-shelf components. We present the current hardware designs and discuss the results of simulation-based experiments involving swarms of up to 1,000 aquatic drones that successfully patrolled a 20 km-long strip for 24 hours.

1 INTRODUCTION

Maritime tasks are usually expensive to carry out due to the use of manned vehicles with large operational crews. While effort has been made to adapt unmanned vehicle technology for use in maritime tasks, such systems are currently relatively expensive to acquire and operate, and only a single or a few vehicles are typically deployed (Yan et al., 2010).

An alternative approach is the use of autonomous systems composed of large numbers of relatively simple and inexpensive drones (swarms). The use of swarms is advantageous given that many maritime tasks such as environmental monitoring, sea life localization, and sea-border patrolling require distributed sensing. The goals of our ongoing HANCAD and CORATAM projects are to overcome fundamental challenges related to communication and control in large-scale swarms of aquatic surface drones. In the HANCAD project, we propose to use a heterogeneous network architecture in which only a subset of the drones are required to carry long-range communication equipment. As part of the project, we will study and develop novel routing algorithms to achieve effective communication in such ad-hoc heterogeneous networks. In the CORATAM project, we propose to use a novel hybrid approach (Duarte et al., 2014a) to the semi-automatic synthesis of self-organized behavior for swarms of aquatic drones. The potential benefits of decentralized control based on self-organization include scalability and robustness to faults (Brambilla et al., 2013), both of which are essential in many real-world scenarios.

In this paper, we present the major components of our ongoing work, namely: (i) the design of our prototype hardware, (ii) the heterogeneous communication approach, and (iii) the methodology adopted for the synthesis of self-organized control. The rest of the paper is organized as follows. In Section 2, we discuss the potential application of swarms of aquatic drones to real-world tasks. We then discuss the challenges, describe our proposed solutions, and the studies conducted so far in terms of hardware (Section 3), communication (Section 4), and control (Section 5). Finally, in Section 6, we discuss our ongoing work and the future prospects for large-scale swarms of aquatic drones.

2 ROBOTS FOR MARITIME TASKS

Aquatic robots have been studied for a wide range of applications including hydrography (Plueddemann et al., 2008), environmental monitoring (Pinto et al., 2014), geology (Lane et al., 1997), archeology (Clark et al., 2008), defense (Clegg and Peterson, 2003), and search and rescue (Furukawa et al., 2006). Over the past decade, significant public and private investment has been made in the areas of autonomous underwater vehicles and autonomous surface vehicles (Manley, 2008; Douglas-Westwood, 2012). The focus has largely been on single-robot systems with a high degree of hardware and software complexity. While these systems have been applied to a variety of scenarios and have proven commercially viable (see, for instance, offerings by Kongsberg[1], Autonomous Surface Vehicles Ltd[2], and Bluefin Robotics[3]), they are expensive and limited in terms of the tasks they can undertake. In particular, tasks involving monitoring, searching, or data collection over large areas typically require distributed sensing capabilities. Distributed sensing can only be achieved by systems composed of multiple, physically independent units such as swarms of aquatic drones.

Land-based and air-based swarm robotics systems have been studied extensively, see Dorigo et al. (2013); Lindsey et al. (2012) for examples, but the same does not hold true for swarms for aquatic environments. While there have been numerous conceptual studies on systems composed of multiple autonomous vehicles for aquatic environments, only a limited number of such systems have been realized. The EU-ICT project CoCoRo (Schmickl et al., 2011) is among a few exceptions. CoCoRo concerns the design and development of a swarm of autonomous underwater vehicles for deep-sea exploration. CoCoRo uses custom-built robots and bio-inspired algorithms for underwater tasks. One of the goals of CoCoRo is to contribute to fields such as biology and metacognition. The aim of our HANCAD and CORATAM projects, on the other hand, is to address the key challenges related to the application of large-scale swarms of aquatic drones in real-world scenarios.

Swarms of autonomous aquatic drones have several potential real-world applications. Coastal countries have, for instance, faced an increased spending on maritime missions over the years. In Italy, the problem of illegal immigration (Monzini, 2007) and organized crime (Lutterbeck, 2006) has contributed to the growth of the Guardia di Finanza's operation. In 2013, the operation's budget[4] amounted to $4.08B and it employed 302 boats, 86 helicopters, and 16 airplanes, as well as a total of 59,335 military personnel (Carta, 2013). In Spain, immigrants crossing the Gibraltar Strait through Morocco led to the implementation of the Sistema Integrado de Vigilancia Exterior (SIVE) in the late 1990s (Lutterbeck, 2006). SIVE relies on military-grade technology such as fixed and mobile radars, infrared sensors, and traditional aquatic and aerial vehicles. Such surveillance and intruder detection tasks could potentially benefit from large-scale autonomous robotic swarms. Furthermore, autonomous drones could be used for non-military operations, such as aquaculture inspection, environmental monitoring, and disaster relief.

In the HANCAD and CORATAM projects, we will design and implement communication and control strategies for swarms of relatively simple and inexpensive surface drones. Drones will be able to communicate through an ad-hoc heterogeneous wireless network. The communication system will allow a remote human operator to maintain a connection with the swarm at all times through a subset of drones equipped with long-range communication hardware. We will use a novel approach that combines evolutionary robotics techniques with manual engineering (Duarte et al., 2014a) to synthesize control semi-automatically. The hybrid technique has the potential to combine the respective strengths of artificially evolving control (Nolfi and Floreano, 2000), namely the automatic synthesis of self-organized behavior, with the benefits of flexible, engineering-oriented approaches in which the experimenter has fine-grained control over behavior.

The primary contribution of the projects will be threefold: (i) we will develop a scalable, heterogeneous, and fault-tolerant ad-hoc network architecture

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[1] http://www.kongsberg.com/

[2] http://www.asvglobal.com/

[3] http://www.bluefinrobotics.com

[4] http://www.rgs.mef.gov.it/VERSIONE-I/Dati/OPENDATA/SpeseBS/

for swarms of aquatic drones, (ii) we will explore our novel approach to control synthesis in a variety of real-world maritime tasks, such as patrolling and intruder detection, environmental monitoring, or infrastructure inspection, and (iii) we will release all software and hardware as open-source, which will allow other researchers to build their own aquatic drones, and to advance the state-of-the-art with respect to the application of autonomous drones for maritime tasks.

3 HARDWARE

One of the main goals of the HANCAD and CORATAM projects is to build prototype hardware to serve as a platform for research and development of swarms of aquatic drones. The platform is planned to be orders of magnitude cheaper to build ($<$ 1000 EUR per unit) than current commercial unmanned surface vehicle, relatively small ($<$ 1 meter in length), and easy to manufacture to allow for large-scale deployment of drones in swarms of hundreds of units or more. We use widely available hardware, and off-the-shelf sensors and motors. Prototype drones will be developed based on open-source hardware and open-source software. Digital manufacturing techniques will be used in order to keep costs low and facilitate adaptation and replication by third-parties. Schematics, 3D models, and source code are available at `http://biomachineslab.com/aquaticdrone`.

We use the Raspberry Pi (Upton and Halfacree, 2013) as the main computing device of each drone. GPS receivers and compasses will provide each drone with localization and orientation information. The drones can be further augmented with sensors for environmental monitoring, sea life detection, and other task-specific equipment, which can be used in parallel with the drone's camera to demonstrate the potential of collectives of aquatic drones.

3.1 Preliminary results and ongoing work

We have experimented with different designs of the drone hull to achieve a good balance between hydrodynamic properties, size, and manufacturability. Currently, we have gone through five iterations of the hull design, see Figure 1. In each iteration, we first designed and modeled a prototype in Rhinoceros[5], and the design was then manufactured in extruded polystyrene foam (XPS) using a 3-axis computer numerical control milling machine. The use of XPS has three main advantages, namely: (i) it is a relatively inexpensive material, (ii) it has a low mass density and it is not porous, and (iii) XPS is easily machinable. Furthermore, we also tested a variety of off-the-shelf components to be used in the drones' propulsion system, such as shafts, motors, and speed controllers. Other components of the robot are 3D printed, such as motor mounts and propellers. In the current prototype (Prototype V), we use the hardware listed in Table 1. The total cost of a Prototype V unit is $\sim$ 260 EUR. In our ongoing work, we are equipping the drones with additional hardware such as retractable nets and water quality sensors, as well as a number of communication technologies, namely Wi-Fi, ZigBee, and WiMAX. In the longer term, we will give drones the capacity to extend their operational autonomy by equipping them with onboard photovoltaic panels.

Table 1: List of hardware in Prototype V

Control	
	Raspberry Pi Model B, 512 Mb RAM
	Kingston 16 Gb SD card Class 10
	TP-Link TL-WN722N high-gain 150 Mbps wireless dongle
Propulsion	
	Two 2213N 800Kv Brushless Motor motors
	Two Turnigy TrackStar 25A speed controllers
	Two 4mm Drive Shaft and 255mm Boat Shaft Sleeve
Power	
	ZIPPY Flightmax 8000mAh 3S1P 30C (for motors)
	ZIPPY Flightmax 5000mAh 3S1P 40C (for everything else)
	Turnigy 5A SBEC switching DC-DC regulator
Sensors	
	Sparkfun MAG3110 triple axis magnetometer
	Adafruit GPS breakout (based on the MTK3339 chipset)

4 COMMUNICATION

One of the main goals of the projects is to enable swarms of drones to operate as a robust wireless sensor network (WSN) where each node is embedded on a low-cost aquatic drone. Mobile ad-hoc networks (MANETs) have been widely studied, see Ko and Vaidya (2000); Chlamtac et al. (2003); Akyildiz et al. (2005) for examples. Studies on MANETs are typically conducted on systems in which nodes are either confined to a relatively small area, or present at densities high enough to practically ensure network connectivity between any two nodes regardless of movement, e.g. Sibley et al. (2002). Scenarios in open environments in which mobile nodes must move to ensure connectivity have been studied. However, the tasks were limited to either maintaining network connectivity, or establishing connectiv-

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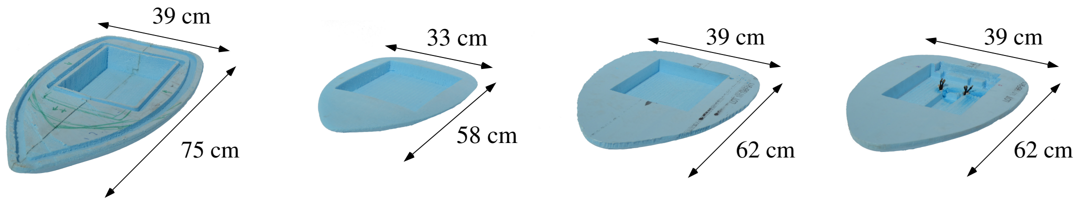
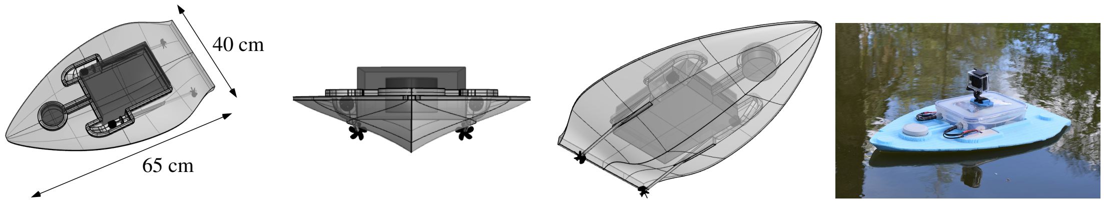
[5] `http://www.rhino3d.com/`



Prototype I Prototype II Prototype III Prototype IV



Prototype V (above) Prototype V (front) Prototype V (below) Prototype V (in water)

Figure 1: Top: Prototype I-IV, bottom: Prototype V, the current iteration of the aquatic drone prototype.

ity between two fixed points. In Winfield (2000), for instance, a swarm of robots must remain aggregated based on connections formed over a low-range wireless network, while in Hauert et al. (2009), aerial robots must self-organize to establish and maintain a wireless network between operators located on the ground.

Distributed sensing over extended periods of time is necessary for several maritime tasks such as patrolling and environmental monitoring. In our design of the communication system, we therefore prioritize autonomy and robustness. To keep the per-unit cost low, we will furthermore use a heterogeneous system of drones: the majority of the drones will only be equipped with relatively short-range communication equipment, while a few, more complex drones, will also be equipped with long-range communication equipment and larger, more expensive batteries. All drones will participate in task execution. The drones with long-range communication capabilities will serve as gateways through which observations can be communicated to human operators and through which operators can issue new instructions. We expect the ratio between the number of simple drones and the number of complex drones to be between 10:1 and 25:1 depending on mission requirements.

Long-range communication can be achieved using high-gain Wi-Fi, 3G/GPRS, WiMAX, LTE, or similar technologies. For missions in which drones need to operate outside the range of terrestrial networks, satellite links could be used. In the HANCAD and CORATAM projects, we are experimenting with high-gain Wi-Fi and WiMAX.

Local drone-to-drone communication can be achieved through a number of existing technologies. In our projects, we will experiment with ZigBee and Wi-Fi, but the specific technology used to establish links between neighboring drones and to push data across can be chosen depending on mission requirements. The key challenge related to the local drone-to-drone communication is to attain mesh-networking topologies that support the dynamic routing between drones with only local communication capabilities and gateway drones. Although there are several ad-hoc routing protocols for networks with changing topologies, we furthermore have to implement opportunistic routing and dissemination: some drones can temporarily be outside the range of the rest of the swarm due to mission requirements and limited communication range. The aquatic environment also poses delivery challenges due to the signal reflections, which must be taken into account in the routing and dissemination protocols. We will develop a custom software layer on top of the low-level wireless protocols to increase robustness and to support reliable connections across an ad-hoc network with constantly changing topology and occasional signal reflections. A comprehensive survey of the challenges and proposed solutions for using wireless communication technologies in sensor networks deployed in marine environments is presented in Xu et al. (2014).

Scenarios in which aquatic drones operate in open maritime environments are challenging because their task is not only to maintain network connectivity, but also to carry out missions that can put constraints on the spatial configuration and motion of the drones.

The heterogeneous nature of the system must be taken into account to ensure that drones with long-range communication capabilities are accessible to the entire swarm. The distance between any drone with only local communication capabilities and a drone with long-range communication capabilities should be kept as short as possible to ensure reliable and timely communication with human operators. If an intruder is detected in a patrolling scenario, for instance, it is important that human operators are notified and can issue new instructions immediately. In our ongoing work, we are studying the interplay between behavior and communication, as well as conducting communication tests in real hardware.

5 CONTROL

Centralized control of multirobot systems, such as swarms of aquatic drones, is attractive because planning, coordination and monitoring can be done based on global knowledge of the system. However, computational and/or communication constraints on the robots may prevent centralized control (Crespi et al., 2008). Moreover, centralized systems tend to be subject to scalability constraints and to be vulnerable given that the central coordinator represents a single point of failure. Systems based on decentralized control, on the other hand, do not have a single point of failure, and when coordination is achieved through local interactions, they tend to scale well, see for example Christensen et al. (2009). Decentralized control based on self-organization is, however, difficult to design by hand because the behavioral rules for individual robots cannot be derived from a desired macroscopic behavior (Dorigo et al., 2004). In the domain of large-scale, decentralized robot collectives, the complexity stemming from the intricate dynamics required to produce self-organized behavior further complicates the hand-design of control systems.

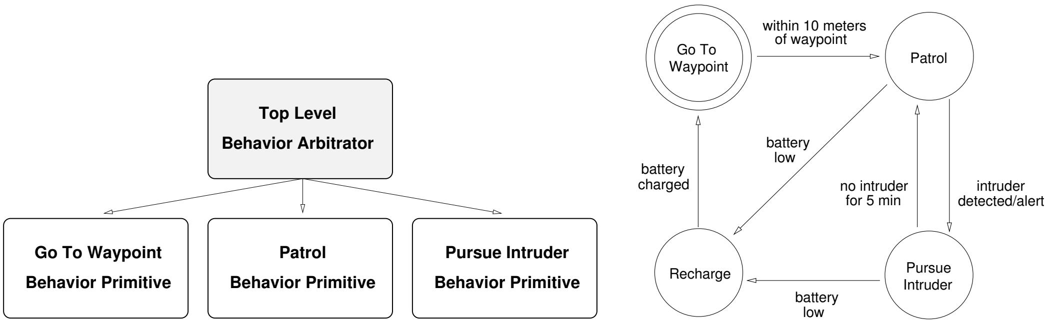
In the field of evolutionary robotics (ER), evolutionary techniques are applied to automate the design of control systems for robots (Nolfi and Floreano, 2000). ER techniques can be employed to synthesize decentralized control for multirobot systems, see Floreano and Keller (2010); Sperati et al. (2008) for examples. Over the years, researchers have identified certain challenges associated with the application of ER. One of the most prevalent challenges concerns bootstrapping the evolutionary process in complex tasks. If controllers for a relatively complex task are sought, evolution may be unable to find a fitness gradient that leads to adequate solutions (Nelson et al., 2009). Another challenge is the use of evolved control in real hardware. Except for a few cases in which evolution is conducted directly on real hardware (see, for instance Watson et al. (1999)), the evolution of robotic controllers is conducted offline, in simulation, due to the large number of evaluation necessary to obtain capable controllers. Simulation-specific features, which are not present in the real world, may be exploited by evolution. As a consequence, the process of transferring evolved controllers to real robotic hardware, known as *crossing the reality gap*, typically fails to preserve the level of performance achieved in simulation (Jakobi, 1997).

Unless very simple tasks are considered, it is difficult to foresee which evolutionary setup might be suitable for solving a particular task (Christensen and Dorigo, 2006). Between the controller, fitness function, and evolutionary algorithm, many different combinations of settings are possible. It then becomes necessary to run the computationally intensive evolutionary process, often multiple times with different initial conditions, to assess if a particular setup produces useful solutions. This leads to a time-consuming trial-and-error process. While a few studies have been conducted in which evolution was applied in a more engineered-oriented manner, such attempts have, so far, been ad-hoc (Silva et al., 2014). Techniques such as incremental evolution (Gomez and Miikkulainen, 1997), incremental robot shaping (Urzelai et al., 1998), and task-decomposition (Lee, 1999; Whiteson et al., 2005) have been proposed, but such approaches do not address the semi-automatic synthesis of behavior in a systematic way.

In our projects, we use a novel, hybrid approach (Duarte et al., 2014a) in which the above-mentioned challenges are addressed by systematically combining artificial evolution, manual engineering, and hierarchical decomposition of behavior. By adopting such an approach, we expect to be able to obtain scalable and robust decentralized control for large-scale swarms of aquatic drones.

5.1 Preliminary results and ongoing work

We have studied a task in which a swarm of up to 1,000 simulated aquatic drones (Duarte et al., 2014b) had to patrol a 20 km-long coastal strip of the island of Lampedusa, see Figure 2. We applied our hybrid approach (Duarte et al., 2014a) for synthesis of control, in which a complete mission can be broken down into a number of simpler sub-tasks until evolution or a human designer can find suitable behaviors. Individual behavior primitives are simple behaviors that are syn-



(a) (b)

Figure 3: Representation of: (a) the hierarchical controller, with one preprogrammed behavior arbitrator and three evolved behavior primitives, and (b) the behavior arbitrator, a preprogrammed finite state machine.

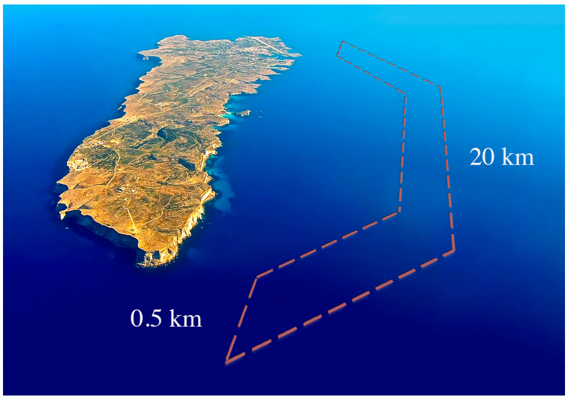


Figure 2: A 20 km-long patrolling zone was used in simulation-based experiments (Duarte et al., 2014b) where up to 1,000 aquatic drones had to execute an intruder detection task. The chosen patrolling zone would be enough to cover the south coast of the island Lampedusa, a major illegal immigration hub.

thesized to solve particular sub-tasks. These behavior primitives are then combined hierarchically using behavior arbitrators, which are decision nodes that delegate control to their sub-controllers. For the patrol task, we evolved three behavior primitives: “Go To Waypoint”, “Patrol”, and “Pursue Intruder”. After the behavior primitives had been evolved, we combined them using a simple state-based preprogrammed arbitrator, see Figure 3. Our initial experiments demonstrated that scalable and self-organized control could be evolved for large swarms operating in an open maritime environment (Duarte et al., 2014b).

Controllers for more complex tasks can have multiple hierarchical layers of both evolved and preprogrammed nodes, allowing for detailed control over behavior. A collection of evolved behaviors can thus be built and potentially reused in different missions. Robotic control for complex tasks can be synthesized in an incremental and hierarchical manner by combining successfully previously evolved/preprogrammed behaviors, while issues related to performance on real hardware can be addressed at each increment. In this way, our approach (Duarte et al., 2014a) circumvents two fundamental issues associated with the application of evolutionary robotics, namely: (i) bootstrapping the evolutionary process, and (ii) crossing the reality gap.

6 CONCLUSIONS

The aim of the HANCAD and CORATAM projects is to study how the fundamental challenges related to communication and control in swarms of aquatic drones can be overcome. We have built five hardware prototypes, we have proposed a heterogeneous networking architecture, and we have conducted the first study on the synthesis of scalable, self-organized behaviors or drones operating in an open maritime environment.

We are currently finalizing the design of the hardware, and we expect to conduct the first experiments on a swarm of real drones before the end of 2014. By the summer 2015, we expect to have demonstrated a system up to 25 operational drones carrying out proof-of-concept tasks such as patrolling and environmental monitoring in water. All software and hardware will be made freely available at `http://biomachineslab.com/aquaticdrone`.

6.1 Future work

In our ongoing work, we continue to study ways in which to increase the capabilities of the drones while still keeping them simple. The simpler the drone, the lower per-unit cost, which in turn allows for wider adoption and/or larger deployments. One of the ways in which the capabilities of drones with relatively simple sensory equipment can be augmented is through the mutual sharing of sensory data through local, situated communication (Rodrigues et al., 2015). The sharing of onboard sensory data between neighboring robots allows individual drones to combine information from multiple sources to obtain information about the environment that would otherwise not be available. The received information can even be used to implement collective virtual sensors, which an evolved controller can use as if they were regular onboard sensors. Initial experiments with collective sensors have produced promising results (Rodrigues et al., 2015).

The limited onboard sensing and processing capabilities may make it difficult for drones to navigate in cluttered environments such as lakes and rivers. To overcome this limitation, the drones could use offline generated semantic maps of the environment. A typical semantic map will indicate which regions of the aquatic environment are closer to the margin, whereas another will pinpoint which regions correspond to shallow waters. The semantic maps could be constructed at the beginning or prior to a mission using a single or a few, sophisticated vessels such as the Riverwatch (Pinto et al., 2014).

As part of our more long-term efforts, we are developing state-of-the-art methods such as the application cooperative co-evolution driven by behavioral diversity instead of a traditional fitness function (Gomes et al., 2014) to synthesize behaviors that enable heterogeneous swarms of drones to maintain connectivity while executing tasks, and online learning in large-scale decentralized systems (Silva et al., 2012).

ACKNOWLEDGEMENTS

This work was supported by Fundação para a Ciência e a Tecnologia (FCT) under the grants, SFRH/BD/76438/2011, SFRH/BD/89573/2012, SFRH/BD/89095/2012, PEst-OE/EEI/LA0008/2013, and EXPL/EEI-AUT/0329/2013.

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