Automated Sensor Fusion-Based Emergency Rescue for Remote and Extreme Sport Activities

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Abstract. I am an abstract - pet me.

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1 Introduction

The recent death of rock climber, alpinist and mountaineer Ueli Steck [10] near Mount Everest is one of the latest reminders of the dangers and risks of remote and extreme sports pursued by athletes around the world. Cohen defines extreme sport as "a competitive (comparison or self-evaluative) activity within which the participant is subjected to natural or unusual physical and mental challenges such as speed, height, depth or natural forces and where fast and accurate cognitive perceptual processing may be required for a successful outcome" [5]. Further definitions focus on potential dangers and risks of extreme sports and define them as follows: "Any sport or recreational activity that is dangerous and, if performed optimally, even by the highly skilled, risks loss of life or limb" [1]. FreeBASE, wingsuit flying, high-altitude mountaineering, free solo climbing, cave diving and whitewater kayaking are only a few examples of such activities. Despite the risks and dangers of extreme sports as well as the high mortality rate, the number of athletes participating in these kind of activities increased over the years - for example, despite the high number of deaths on Mount Everest in recent years, the number of climbers and ascents of earth's highest mountain (8848m) has increased almost every year [11]. In 2017, a record number of permits was issued to climbers and mountaineers that aim to scale Mount Everest [6].

Limiting and controlling risks as well as providing support in case of emergencies are among the key concerns of conducting extreme sports. Even though the technological advances of the last decades changed and improved our daily lives in various ways, the risks and dangers of extreme sports still persist and pose challenges to even advanced technologies [2][12][20]. The harsh conditions and remote locations of extreme sports result in challenging requirements for all kind of involved hardware. The lack of easy access to power supplies as well as the extreme temperatures, humidity, altitude and socio-technical limitations impede the design of hardware devices for extreme sports. Despite those difficulties, some sensor-based devices provide different types of support to athletes, e.g, satellite phones, avalanche transceiver or satellite emergency notification devices (SENDs) such as the SPOT Gen3[3], but compared with nowadays high-tech devices of our daily live, their capabilities are very limited.

Over the last years, research focused on sensor-fusion based activity recognition (e.g., [25][26][15]) in combination with alarm-systems for elderly persons (e.g., [14][27][7][22]) in order to support their daily live especially in case of emergency. To our knowledge, research of these technologies has never been applied and used in context of extreme sports or similar fields. Using sensors and sensor-fusion to monitor activities of athletes can be used to detect (potential) emergency situations and/or accidents and sending automated emergency calls in case the athlete is impeded from doing so. In the context of extreme sport activities (ESAs), this is still considered an open issue. Therefore, this whitepaper addresses the identified gap by investigating the technical feasibility of sensor-based hardware devices that support extreme sport athletes and thereby answering the research question: How to enable automated sensor fusion-based emergency rescue for remote and ESAs? In order to establish a separation of concerns, we furthermore pose the following subquestion: What challenges are posed by remote and ESAs and what are the technical requirements and limitations? What are example use cases and scenarios? What are the specifics of an exemplary emergency fall detection device for climbing activities?

The remainder of this whitepaper is structured as follows: Section 2 focuses on the difficulties and challenges posed by ESAs as well as the role and potential of information technology in such activities. Section 3 deals with example use cases and scenarios used to derive technical requirements and functionalities of emergency devices for ESAs. The technical requirements are discussed in Section 4. Section 5 introduces a prototype implementation of a emergency fall detection device for climbers, followed by the evaluation of the prototype in Section 6 and a discussion on potential enhancement of the prototype for broader applications. Section 7 concludes this whitepaper together with discussing limitations, open issues and future development work.

2 Dimensions and Roles of Technology in Extreme Sports

Understanding the different dimensions and roles of any kind of physical activities supports the proper design and development of new hardware devices for extreme sport athletes. For this purpose, we utilize Mueller and Pell's [13] two dimensional categorization of roles in adventure technology. Based on [23][16] and in accordance with [4] and [9], Mueller and Pell define adventure as an "exciting experience involving hazardous action with uncertain outcomes based around physical exertion in a natural environment" [13]. Furthermore, they define adventure technology as "technologies that aim to support the adventure, whether they were designed for the adventure or not (for example, adventurers might chose to use high-end smartphones for their expeditions although they are

[3] `https://www.findmespot.eu/en/`

designed for corporate work, often resulting in devastating consequences when they break or lose connection)" [13]. Note that Mueller and Pell's definition of adventure is slightly different from the definition of extreme sports introduced earlier in Section 1. If we exclude Mueller and Pell's constraint of the *natural environment* and then comparing both definitions we come to the insight, in context of this whitepaper, that adventures are an essential part of ESAs - even though the opposite is not true. As a result, we argue that adventure technologies as defined above do not only support adventures but can also be used to support ESAs and therefore their two dimensional categorization of roles in adventure technology can also be used for technology supporting ESAs.

2.1 Dimensions of Technology in Adventures

As illustrated in Figure 1, the first dimension relates technology to instrumental and experiential aspects of adventure, whereas the second dimension focuses on the expected and unexpected aspects of adventures.

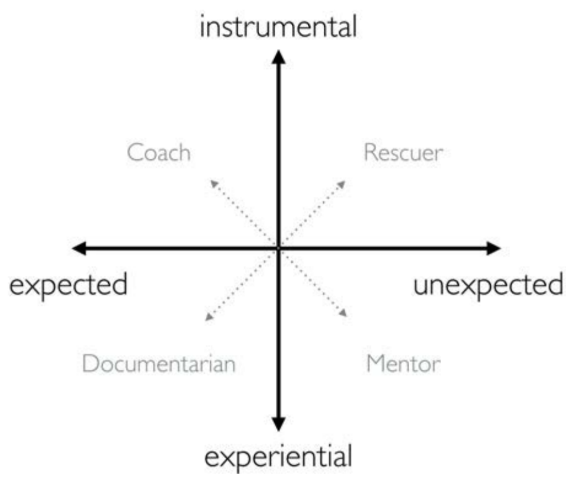

Fig. 1: Four roles adventure technology (Source: [13])

Instrumental technology helps the athlete or adventurer to achieve tangible goals and improve performance [24][17]. Typical examples are quantified-self products such as pedometers, Zlagboards[4] for climbers and similar devices.

Experiential technology represents the other end of the first dimension and focuses on technology that supports the adventure experience, such as enabling a deeper engagement with the environment or a richer way of sharing the adventure story, according to Mueller and Pell [13]. We further argue that information and data collected by experiential technology is even more valuable for the purpose

[4] `https://www.zlagboard.com/`

of planning, logistics and knowledge exchange - either for the athlete him/herself or fellow athletes.

Expected situations are part of every sport activity or adventure and technology supports users in such scenarios, e.g., using a GPS tracker for proper navigation in unknown environments.

Unexpected situations are far more difficult to prepare for by definition and often leads to "using technology for purposes that had not been considered before" [19]. Mueller and Pell describe an example of "hacking" a 2G mobile phone to receive BBC updates about an earthquake by inserting a piece of wire into the audio port of the phone and creating a shortwave magnetic loop around the device to receive BBC Life Line updates via shortwave radio frequencies [13].

2.2 Roles of Adventure Technology

Based on the two dimensions, Mueller and Pell articulate four roles (coach, rescuer, documentarian, mentor) that technology can play during adventure, as illustrated in Figure 1. The *coach* technology provides structured guidance in expected situations to improve instrumental aspects, e.g., enhancing performance or providing experience.

Furthermore, technology can also take on the role of a *mentor*. The mentor provides the athlete or adventurer with guidance and support for critical reflection, thereby stimulating the adventures opportunity for personal growth [8].

The technological role of a *documentarian* is most commonly fulfilled by cameras or similar recording devices capturing experiential aspects. Mueller and Pell mainly focus on self-expression and storytelling aspects, whereas we would like to emphasize less subjective aspects: Using a broad variety of sensor-related devices to capture as many information of the surrounding environment as possible, as well as internal attributes of the user itself. Such data does not only serve as a documentation of achievements, but also provides valuable insights during later analysis that can lead to further performance improvements, risk minimization, risk avoidance or for the planing and logistics of future adventures and projects.

The most relevant role of technology in the context of this whitepaper and most extreme sport athletes is the role of the *rescuer*. Providing support in case of emergency or having access to emergency services during unexpected situations is a key concern of this work in order to minimize the risks of loss of life, limb or any other serious injuries. As mentioned earlier, satellite emergency notification devices (SENDs) such as the SPOT3 (illustrated in Figure 2) already provide basic emergency services by manually pressing an emergency button, but due to the complexity and physical exertion of ESAs, an automated emergency systems is potentially able to further minimize risks for extreme sport athletes.

Fig. 2: SPOT 3
(Source: https://www.findmespot.eu)

As argued above, the presented two dimensional categorization of roles in adventure technology of Mueller and Pell can be applied to technology supporting ESAs in a similar manner. In the following Section 3, we provided different examples of ESAs and corresponding use-cases and scenarios where technology can support athletes. The categorization and role system presented above is used to analyze existing technologies that support the examined ESAs as well as to guide the development of our own emergency rescue system as a result of this whitepaper.

3 Use-Cases and Scenarios of Technology in Extreme Sports

In the previous Section 2, we presented a two dimensional categorization of roles in adventure technology and how technology can support ESAs in a theoretical manner. This section introduces some example ESAs from different categorizes of sport activities. For each example, application use-cases and scenarios on how technology can support the athletes is described, followed by mapping the results to Mueller's and Pell's two dimensional representation system for adventure technology. In the context of this work, we focus on the issue of support in emergency situation and how technology can help athletes in such situations.

First, in Section 3.1 we consider climbing and mountaineering activities, followed by ultra-distance ESAs in Section 3.2. Section 3.3 and Section 3.4 focus on water and air-based ESAs. The final section 3.5 focuses on so called poly-athletes. For each of this section, we only consider example use-cases and scenarios for illustration purposes without claiming completeness.

3.1 Climbing and Mountaineering

For the purpose of this section, we spare to participate in the discussion on the differentiations between climbing and mountaineering, since both pose similar use-cases and requirements. In the context of this work, mountaineering refers to scaling or ascending mountains or hills where the use of technical equipment is essential for either hands or feet [3]. Climbing refers to ascending rocks, cliffs or similar natural structures where technical equipment is only used for security purposes. We exclude indoor climbing and/or bouldering on artificial climbing structures (ACS). Rotillon [18] argues that climbing cannot be considered as an ESA, since everything in climbing is done to eliminate deadly risks. But according to our definitions of extreme sports in Section 1, the reduction of risks has nothing to do with the fact of an activity being considered as extreme sport.

Most of serious injuries of climbers are caused either by downfalls of the climber or falling rocks [**?**]. The later, can be partially prevented by using helmets or avoiding climbing areas with loose rocks, but downfalls are an essential part of climbing - especially at later stages when pushing (personal) limits. Similar issues apply to mountaineering, but in addition extreme low temperatures and oxygen deficiency caused by high altitudes pose further risks. How can technology support climbers and mountaineers during ESAs, especially in emergency situations the context of the role of a rescuer?

First of all, notifying relevant entities about the emergency using the same technique as provided by satellite emergency notification devices (SENDs) is the first crucial step. Devices such as the SPOT3 (Figure 2) and SPOT Gen3 are capable of sending emergency notifications after manually pressing the corresponding button - transmitting the exact location of the user via satellite, based on GPS information or similar systems. But manually pressing the emergency button might not always be possible in case of an emergency. The device might be stored in the bag of its user and out of reach, or the user is seriously injured and not capable of pressing the button or for any other reason. Therefore, combing state of the art systems with sensor fusion-based techniques for activity recognitions enables us to detect emergency situations and automatically sending an emergency notification. For example, acceleration sensors are used to monitor moves and activities of the user. In case of a downfall, it is possible to detect the unusual and fast relocation of the user. Of course, not all downfalls are relevant, therefore the device considers only falls of a certain height (e.g., more than ten meters) or downfalls with following inactivity of the user which might indicates injuries and incapability of further motions. In order to avoid false alarms, the device announces the detection of a potentially serious fall by emitting a loud alarm signal - if the user starts moving again, the device recognizes the false alarm and does not send the emergency notification. Similar approaches are used in order to prevent death by hypothermia or lack of oxygen during high-altitude mountaineering. In case the sensor device detects no further motions of the user in combination with potentially dangerous temperatures and/or a certain altitude (indicator for lack of oxygen), the device emits the alarm sound and if not deactivated in the same manner as described above, the emergency notification is transmitted via satellite.

Besides the support in emergency situations, technology can also take over the role as a mentor, e.g., while scaling most mountains, it is necessary to reach the peak before a certain time of the day, otherwise the empirical probability of death rises significantly since the athlete does not have enough time to get down to the base camp or the slow progress during the ascent already suggests an insufficient level of physical fitness which might lead to serious injuries or death. Therefore, technology can be used to remind the athlete to start descending in case that the peak has not been reached in time. Moreover, the role of a documentarian is also supported by collecting data during ascents and descents as well as climbs that can later be used by athletes for analysis, planing, training and preparations.

3.2 Ultra-Distance ESAs

Work-In-Progress: Complete later if necessary.

3.3 Water-based ESAs

Work-In-Progress: Complete later if necessary.

3.4 Air-based ESAs

Work-In-Progress: Complete later if necessary.

3.5 Poly-Athletes

Especially extreme sport athletes tend to exercise a variety of different or complementary ESAs on an elite level that only few people are capable of. We refer to those athletes or persons as *poly-athletes*. Usually, persons referred to as adventurers of ealier decades or centuries belong to this categories since most of their projects required a diverse and multi-facet skill set. The English explorer Ranulph Fiennes is one of them, crossing both poles, scaling Mount Everest, climbing Eiger by its North Face and journeying around the world on its polar axis. In more recent years, athletes such as Dean Potter (Climber, alpinist, BASE jumper, FreeBASE, highliner) or Anton Krupicka (Climber, ultra distance runner and cycler,) and many more belong into this category. But even on a more basic level, many dedicated sports persons tend to pursue more than one activity, thereby opening the opportunity to developing support devices that can be used for different activities - switching activity recognition and alert settings of the device as well as the technology roles depending on the exercised activity.

4 Technical Requirements and System Architecture

The design and development of hardware for harsh outdoor conditions is a challenging task [**?**], even with nowadays high-tech materials. Similar to the extreme sport athletes, the supporting hardware devices have to withstand extreme weather conditions and cope with hostile environments. Defining and evaluating the technical requirements of the supporting hardware devices is the focus of the following Section 4.1. Afterwards, Section 4.2 describes the general architecture that we propose for hardware devices that support ESAs in use-cases and scenarios that we outlined earlier in Section 3.

4.1 Technical Requirements

Work-In-Progress

4.2 System Architecture

Work-In-Progress

5 Prototype Implementation of a Fall Detector for Climbers

Based on the analysis conducted in Section 3.1, the design and development process of a prototype for a downfall detection during climbing activities is outlined in this section. First, Section 5.1 provides a short introduction to downfalls during climbing activities. Afterwards, the utilized hardware and configuration is presented in Section 5.2, followed by the implementation in Section 5.3. An evaluation is conducted later in Section 6.

5.1 The Theory of Downfalls

Downfalls are an essential part of climbing, especially when pushing personal limits. Most downfalls have no consequences at all and the climber continues climbing almost immediately. Climbers clip their rope into several carabiners (connected with the wall/rock) while climbing in order to keep the length of falls to a minimum. However, this is not always possible and in several regions it is not possible to place such protections at all, the distance between two consecutive carabiners is quite long or protection fails and therefore extends a downfall significantly. But a downfall is not only defined by its length. Further important aspects concern the angle of the climbed wall - is it a vertical wall, is it an overhang or is the wall (slightly) inclined thereby creating a slab? Depending on the wall's angle, the climbers acceleration during a fall might differ due to friction. In addition, the number of clipped carabiners and the angle between rope and carabiners adds further friction, thereby lowering the speed of a fall. Moreover, climbers use dynamic ropes that elongate in case of a downfall. Nowadays climbing ropes elongate between 28% to 35% (dynamic elongation). Finally, experience and behavior of the belayer also influence the downfall either in a negative or positive manner.

All these factors have to be taken into account in combination with further external properties of the surrounding environment, in order to estimate the risk posed by a downfall. Therefore it is difficult to label certain falls as potentially dangerous and others as harmless. As a result, we provide a configuration interface to the user in order to adapt to external factors. For example, the user can configure the length of a fall that is recognized as potentially harmful and the number of acoustic warnings played to the user before sending an emergency notification. If the climber starts moving again, the emergency notification is canceled and the downfall marked as not harmful.

5.2 Hardware

In order to implement the prototype we chose a simple and customizable setup. As illustrated in Figure 3, a Raspberry Pi 2 Model B with Debian is used as a computation platform and powered by a mobile battery pack. The MPU-6050 3-axis accelerometer sensor is attached to the Raspberry Pi and provides 3 dimensional acceleration data. The setup is placed in a small bag and attached to

Fig. 3: Hardware overview: Raspberry Pi 2 Model B, MPU-6050 3-axis accelerometer, portable battery pack

the climber's harness while climbing. The demonstrated prototype does not contain any functionalities to actually send emergency notifications or play acoustic warning signals. Both functionalities are left out in order to ease the prototype development.

5.3 Prototype Implementation

The prototype is implemented based on the hardware and configuration described in the section above. When powered on, the device starts collecting

3 dimensional acceleration data. The collected data is further processed using Kalman filter [?] in order to smooth the recorded data before further processing it. Subsequently, the smoothed data records are analyzed in order to detect relevant acceleration deviations that indicate a misplacement (downfall) of the device. In case the misplacement exceeds the pre-defined value for potentially dangerous downfalls, a notification is send to a monitoring website. In case the climber does not continue his climb at some point after the misplacement, a further symbolic emergency notification message is send to the website.

Future iterations of the prototype might include additional sensors for sensor-fusion based data analysis and further monitoring devices such as smart watches in order to ease testing of the system.

6 Prototype Evaluation

Action design science [21]

6.1 Evaluation

Work-In-Progress

6.2 Limitations

Work-In-Progress

6.3 Related Work

Work-In-Progress

7 Conclusion

Work-In-Progress

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