Generating Research Aims for Legged Robots: a Market and Dependability Approach

H. Doran, *Member IEEE,* F. Hannich

***Abstract*— We content that real-world widespread adoption of multi-legged robots is not due to some magic missing engineering ingredient but due, by and large, to two related factors. The first is that the market must be educated as to the potential benefits of such technology and secondly any missing engineering ingredients need to be market derived and not research specified. After discussing the issue of educating the market we proceed with an example of generating market-oriented technical requirements which specifically result in new controller architectures. We continue this example with two examples of requirements generated by technical analysis, including Systems Theoretic Process Analysis, and so show that whilst the continuation of fundamental research is necessary if multi-legged robots are to find a sustainable set of real-world applications research resources need to be guided into market research and market orientated industrialisation.**

I. Introduction

The exemplary quadrupeds come from Boston Dynamics a company that received substantial funding for the development of a combat-capable troop robot which went into storage in 2015 [1]. There are no announcements on the Boston Dynamics site that mention any real-world applications [2], a remarkable situation given the company was recently purchased for around 100 million USD [3]. The technical sophistication, judging by publications and promotional material [4][5] is such that one might assume the quadrupeds only need fitting to specific applications. The lack of observable applications is troubling for this kind of technology, it might be due to a poor basic functionality or it may be that the lack of applications are informing research in the wrong direction.

On the other end of the scale challenges, such as disaster response [6] or service robotics [7], have long been the standard method of encouraging focused research in robotics; however these challenges operate on two levels. Whilst challenge fulfilment and indeed individual task fulfilment within the challenge requires a high level of research these challenges represent postulated markets and use-cases. One effect that this has is the lingering suspicion that many papers simply iterate the list of challenges as possible uses for their work without having really considered the potential markets and therefore any real-world requirements that their work may have to fulfil.

H. D. Doran is with the Institute of Embedded Systems, Zurich University of Applied Sciences, Winterthur, Switzerland. (phone: +41 58 934 76 76; fax: +41 58 935 76 76; e-mail: donn@zhaw.ch)

F. Hannich is with the Institute of Marketing Management, Zurich University of Applied Sciences, Winterthur, Switzerland. (e-mail: hanf@zhaw.ch)

This incongruence motivates this paper where we examine the issues from an application oriented view and generate engineering requirements, in this particular case controller architectures, from a marketing and a dependability oriented approach. This informs the structure of the paper. We discuss the issue of educating the market and generating a plausible use-case in the next section ending up with some technical requirements. In Section III we discuss generating controller architectures and in Section IV we conclude, discuss and propose further work.

II. Harnessing Marketing Methodologies to Generate Technical Requirements

A. Educating the Market

The idea of market education is a well-known concept in marketing, potential customers need to understand what the product is, what it is for and how it will benefit them if they purchase it. What may be obvious to a researcher is not necessarily obvious to a potential customer. A company needs to position a product in the mind of the customers and create a unique selling proposition (USP) from a customers' perspective [8]. Even if the potential customer can imagine purchasing such a product then new product still exhibits an adoption lifecycle, modified convincingly by Moore [9] with his idea of a chasm between the early adopters and the early majority. Given the lack of published real-world applications the authors would place legged robots in the innovators phase Figure 1. This curve tells us that for market success it is not only important that superior features technically exist, but also that customers realize these superior features and value them. Only then, they will be prepared to actually pay for these features. This makes it very important to know customers preferences and one would ideally integrate customers into the innovation process. This ranges from market research such as customer focus groups on product requirements or prototypes to fully integrating customers in a co-creation setting. The importance of integrating customers early into innovation processes has been emphasized by design thinking approach [10], which has been introduced into engineering education for some time [11].

To find some applications we can turn to some conventional marketing methods.

B. Market Orientated Technical Requirements

There are some fundamental assumptions that can be made to generate some initial key figures of reasonable accuracy and provenance. Assume a quadruped robot. The robot weighs 25 kg. The fundamental benefit of a compliant robot is that the load mass is in the same region as the mass of the robot, in this case say 25 kg. Assume a stiff robot like the UR 5 with a payload of 5 kg and a retail cost of roughly 19'000 €. Assume UR make a healthy profit and produce robot arms in reasonably sized lots. The pricing translates into an average rounded cost (to the end-user) of 3'200 € per axis. Translated into a quadruped with three drives per limb this equates to a retail cost of 38'400 € per quadruped. This is quite obviously an underestimation but a useful working figure. We have thus generated two targets. The first is for engineering to achieve a retail cost of 38'400 € per quadruped or lower. The second is for marketing to find a use-case where the value of the work achieved by transport loads of 25 kg over a suitable amortisation time period is worth more than 38'400 €.

To do the second an applicable method is to use a spider-web diagram as shown in Figure 2 for the use case of a generic transport vehicle. The aim is to graph the comparative advantages of one potential product versus others in that market. A large part of the information quality from such a diagram stems from a useful naming of the axis, which of course can be chosen to maximise the comparative advantages of the technology vis a vis competitors. In this example we map a quadruped robot against well-understood wheeled and tracked technology. The quadruped has clear advantages with respect to autonomy, difficult terrains and in causing less damage to the terrain it walks on.

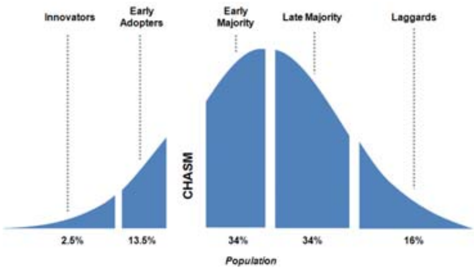

Figure 1: Technology Adoption Life-Cycle as proposed by Moore. The difficulty of getting products mainstream is to find and present product advantages to the early majority as the innovators and early adopters generally will see the benefits of the technology themselves and wish to use it to solve their own real-world problems.

Figure 2: Spider-Web diagram for a quadruped. With three clear and one conditional technical advantage market relevant use-cases can be determined.

The top three rated features make the legged robot ideal for rough and agricultural terrain. It also makes the robot suitable for surface-crossover applications outdoors/indoors concrete/carpet because the feet can be cleaned easier than tracks or tyres with profiles. A 25kg load capability is just enough to do something useful – airlines typically mark suitcases over this weight as "heavy." A quick brainstorming session helped postulate two possible uses. The first is a box carrier used by removal firms, this robot would have to be able to navigate autonomously and repetitively from van to apartment door and from apartment door to whichever room the box is required. The sticking point here is whether a quadruped cost of 38'000 € justifies its investment in an industry typified by day-labourers and cash-in-hand payment practices. The second potential use-case is a precision weed-killer of the sort favoured by many companies recently – albeit using wheeled and tracked robots [12] [13]. The advantage of a legged robot in each case is the ability to navigate different and challenging terrains without damaging the terrain (carpeted stairs, soft agricultural land.) Both robots would need some kind of intelligent load-harness, need to function under shifting load conditions, have some degree of autonomy in navigation and require optimised power management. The moving robot strikes us as exposing more interesting technical challenges so we decided to continue with this. As this robot is a piece of machinery it must also conform to the relevant machine safety norms, IEC 61508.

Note that despite the qualitative nature of the analysis the focus has been shifted towards benefits for specific users and a use-case that bears further analysis to determine its marketability rather than a generic use-case like emergency response.

III. Generating Controller Architectures

In order to develop controller architectures for the quadruped we use System Theoretic Process Analysis (STPA.) STPA is a methodology developed by Leveson [14] for the safety-relevant analysis of technical systems. It models a system as a holistically considered socio-technological system and safety, including dependability, as an emergent property.

At first a functional model of the system, by representing it as a hierarchical control structure, is required and for this we need to determine the man-machine interface. The use-case is high on collaboration (robot-human) but not cooperation (robot-robot). We imagine the autonomy as follows: the robot must be guided from the removal van to the point of entry of the apartment. Once inside the apartment the robot may be guided to each of the rooms either at once or on demand. From this time on it must find its way between the van and the point of entry autonomously and inside the apartment to the correct room on demand.

A. *Controller Architecture*

Guided by this conception the hierarchical control structure features two main controllers and three sub-controllers (Figure 3.) C1, the human controller, is the on-site controller that uses and guides the quadruped. C2 is native to the robot and controls the autonomy of the quadruped. There are three processes. The task process CP1, the collision avoidance process CP2 and the environment scanning process CP3. The controllers are stimulated by control actions (CAn) so in this example C2 would receive a feedback from the environment scanning system that there is the danger of a collision. C2 would then trigger the control process Collision Avoidance to take remedial action according to whatever policy CP2 is initialised with. Of course the principle of hierarchical control applies to the autonomous controller as well so that C2 may consist of multiple controllers.

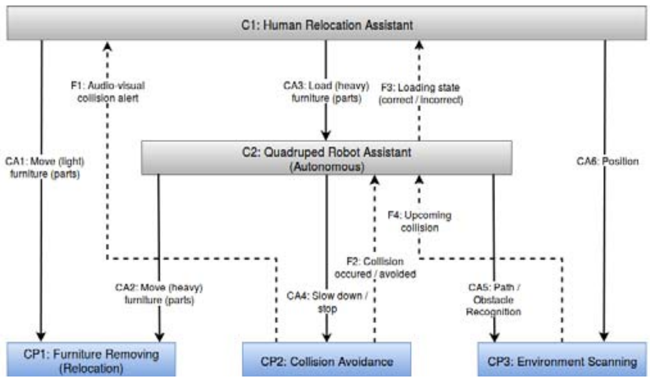

Figure 3: Hierarchical control structure for a semi-autonomous removal robot

The next step is to examine the control actions to make sure they are all safe. Normally we would assume that the control action arrives at the process in a timely and correct fashion. What we wish to look at here is what happens if this is not the case so we ask standardised questions pertaining to the effects on the system if control actions are applied at, for instance, the wrong time or the wrong value. It is also an opportunity to develop and optimise the controller architecture and so increase robustness. The control actions are taken from the hierarchical control structure and in an example we take Control Action 2 (CA2.) The analysis results are shown in Table 1. The first case CA2.NP means control action 2 Not Provided. Not provided means that no control action is taken at all which would be the case, for instance, if the power source suddenly failed.

Table 1: Unsafe control actions and their effects

ID	Keyword	Description
CA2.NP	Not provided	(Energy loss) Robot stops working in unsafe position (e.g. collapsing) - load might be damaged
		(Energy loss) Robot stops working in unfavorable position (e.g. stairs) - hard or dangerous to unload
		Technical defect - heavy load has to be carried/moved by a human relocation assistant
CA2.PNE	Provided when not expected	Robot moves unintentionally (without being loaded)
CA2.IP	Incorrectly provided	Robot takes wrong path - does not reach target location
		Robot collides with obstacles or humans
		Robot starts moving procedure without enough battery capacity to fulfill the task
		Robot stops working in unsafe position (e.g. collapsing) - load might be damaged
		Robot stops working in unfavorable position (e.g. stairs) - hard or dangerous to unload
CA2.PTE	Provided to early	Robot starts moving without being properly loaded
CA2.PTL	Provided too late	Robot does not start moving after properly loaded - efficient workflow of relocation is impaired
CA2.STS	Stopped too soon	Robot stops moving before reaching target location - manual moving to target location needed
CA2.ATL	Applied too long	Robot does not stop moving at target location / walks too far - manual moving back to target location needed

The next step is to generate a control diagram which includes the mitigations for the determined unsafe control actions. We see this in Figure 4. Three points in this figure deserve further comment. The first is that sudden power loss – out of control of the quadruped controller – leads automatically to an emergency stop which in turn must activate a mechanical emergency locking because the quadruped would otherwise simply fall over possibly damaging itself and its load. All other actions – walking or stop on demand are handled via the motors, this means walking and stopping or waiting to be loaded/unloaded or going into a controlled safe position because of failing power, it does not mean stopping for an impending collision as this is handled in CA4 of the hierarchical control structure. Since the robot shouldn't simply wait until the power fails, in the course of multiple discussions it was decided that power management (we assume a battery powered robot) was a non-negligible process as both a state and predictive component is required. The control loop is shown below in Figure 5 while Figure 3 would need appropriate updating.

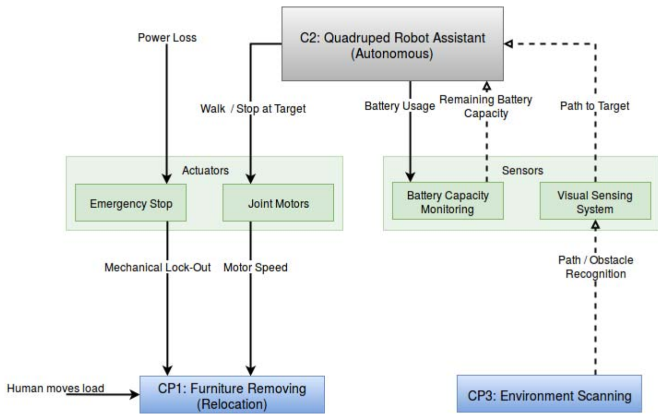

Figure 4: Controller architecture for the task furniture removal and environmental scanning

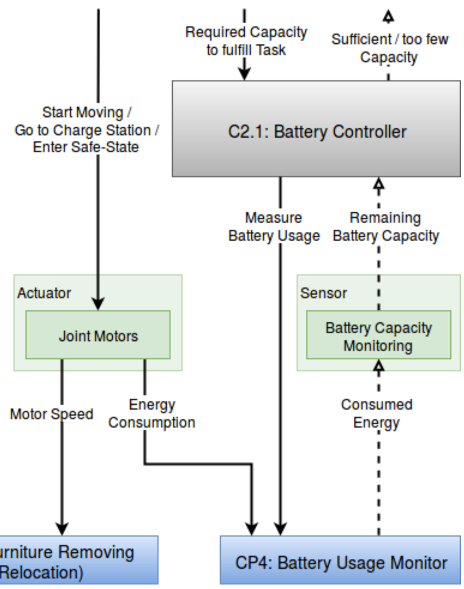

Figure 5: Control loop for the battery controller

B. *Controller Architecture Implementation*

A standard safety and dependability analysis; generation of a preliminary hazard list; analysis of the list and determination of mitigations; determination of a safe state and design of the safety function to bring the device into the safe state [15] – was performed. In this case the safe state was determined to be that the robot finishes its step and sinks into a crouching position. This series of actions requires substantial power so the power management referred to earlier must take this feature into account. Further analysis determined that the leg controllers should be distributed using ring topology real-time Ethernet– i.e. one controller at each shoulder. This topology also has the effect of reducing the computing load on the main CPU. The proposed design can be seen in Figure 6.

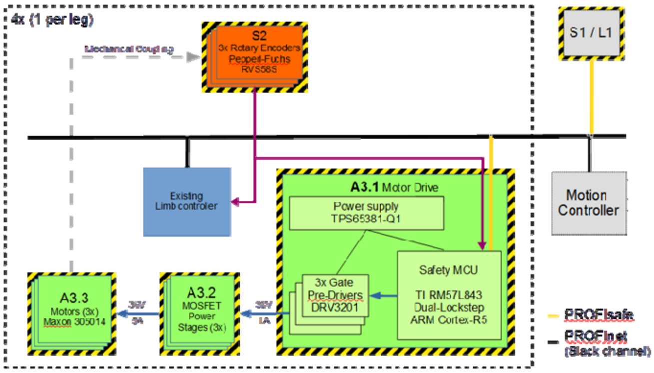

Figure 6: Distributed leg controller architecture. The motion controller is centralized and connected via a ring real time Ethernet. The limb controller could be integrated within the safe Motor Drive

IV. Discussion

We have shown that using structured and easily understandable and applicable marketing tools we can quickly define the technical parameters for a marketable use case for legged robots. From this use-case we can also precisely determine research and engineering requirements down to controller architectures. To generate a conceptual architecture we used STPA. To generate a concrete architecture we used classic safety and dependability analysis techniques which converged on a distributed controller architecture. We contend that the controller architecture generated by a well-considered STP analysis is better structured, more robust and, due to its modularity, more likely to be incrementally extendable than any ad-hoc architecture.

We also contend that our initial argument, that the use of this methodology is more likely to converge towards higher adoption rates of legged robots, whilst simultaneously encouraging high-quality research than requirements generated by any other fashion. We also suggest that despite generated requirements being use-case specific, many are also applicable on a more general level.

As we began our discussion with a market-orientated perspective and we trace the design from initial requirements to a concrete architecture the question is raised as to what extent is implementing our suggestions engineering, applied research or research work. If we examine the power issue mitigations, providing a mechanical lock-out is clearly engineering. Providing an intelligent harness for loads is in the realm of applied research. Ensuring the robot can handle sudden or rhythmic load shifts, as would happen when carrying liquids, or provide continuously updated estimates for power usage and management, is clearly a research task.

We conclude by pointing out that what has been proposed here is a short-form of a disciplined process and we only present an incomplete example. We would propose that senior researchers decide upon a use case and apply this methodology to generate a complete controller architecture from which a list of research aims in control, actuators and sensory systems can be generated.

Acknowledgment

Thanks are due to Thomas Müller for the creation of the STPA diagrams in this paper.

References

[1] https://www.military.com/daily-news/2015/12/22/marine-corps-shelves-futuristic-robo-mule-due-to-noise-concerns.html last accessed 20.08.2018

[2] https://www.bostondynamics.com/news last accessed 20.08.2018

[3] https://www.ft.com/content/22827134-4cb2-11e7-a3f4-c742b9791d43 last accessed 20.08.2018

[4] D. Wooden, M. Malchano, K. Blankespoor, A. Howardy, A. A. Rizzi and M. Raibert, "Autonomous navigation for BigDog," *2010 IEEE International Conference on Robotics and Automation*, Anchorage, AK, 2010, pp. 4736-4741

[5] https://www.bostondynamics.com/robots last accessed 20.08.2018

[6] https://eu-robotics.net/robotics_league/erl-emergency/about/index.html last accessed 20.08.2018

[7] https://eu-robotics.net/robotics_league/erl-service/about/index.html last accessed 20.08.2018

[8] R. Reeves, Reality in Advertising, New York. 1970.

[9] G. Moore Crossing the Chasm, Marketing and Selling Disruptive Products to Mainstream Customers, Harper Business, New York, 2014

[10] Brenner, W., Uebernickel, F., Abrell, F. "Design Thinking as Mindset, Process and Toolbox" in: Brenner, W., Uebernickel, F. (Eds.) Design Thinking for Innovation, Springer, Cham. 2016

[11] Hoyer, W.D., Chandy, R., Dorotic, M., Krafft, M., Singh, S. "Consumer Cocreation in New Product Development", Journal of Service Research, Vol 13, Issue 3, pp. 283 – 296, 2010.

[12] https://qz.com/553383/this-robot-kills-weeds-and-could-end-the-need-for-herbicides-on-farms/ last accessed 20.08.2018

[13] D.C. Slaughter, D.K. Giles, D. Downey, "Autonomous robotic weed control systems: A review," Computers and Electronics in Agriculture, Volume 61, Issue 1, 2008, Pages 63-78.

[14] N. Leveson. Engineering a Safer World: Systems Thinking Applied to Safety. MIT Press, 2011

[15] C. Ericson. Hazard Analysis Techniques for System Safety. Wiley, 2005