Using Design Science Research for Development of a Neutron Monitor

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***Abstract*— Neutron monitors are essential instruments for measurement of neutron radiation through earth's atmosphere. In order to measure radiation, it is possible to perform neutron counts at specific locations on earth. These measurement locations are often remote and in challenging environments, leaving the designer of such instruments with a range of design challenges. In order to design a neutron monitor, it is necessary to analyze the real-world problem and conduct research to reduce development risk. This paper describes the process that was followed to develop a neutron monitor and the North-West University as a collaborative effort between the Faculty of Natural Science and the Faculty of Engineering. Development commenced with an analysis of an AS IS neutron monitor, in use at the onset of the project. A road map was developed in the first research project to prioritize development efforts as a series of research projects. The ensuing research projects were used to systematically address risks and issues, and to follow a development approach based on Systems Engineering (SE) and Design Science Research (DSR), where relevant physical artifacts are delivered as a means of validation. Lessons learned from this collaborative effort are provided to aid future decision making and planning in research management.**

Keywords*— *Neutron monitor, Design Science Research, research and development

I. INTRODUCTION

Successful implementation of artifacts resulting from research efforts (particularly at academic institutions) has singular challenges. For example, it is a challenge to ensure continuity in a development project that is a cost-intensive activity, and risks are often encountered in the form of resource availability, continuity, and quality of deliverables. This is often due to research students being employed as designers to save on development cost, with these students continuously entering and leaving the development project. Students require research direction, and research managers (also acting as development managers) do not have time and skills to support applied research efforts. Understandably, research managers and leaders are inundated with teaching and learning commitments, administrative tasks and own research to the extent that focus on development is not possible – this introduces research and development risk that inevitably cause unnecessary delays and potentially lack of quality.

In order to address risks in academic research and development (R&D) projects, it is possible to combine research *and* development by using Design Science Research [3 - 7] as a paradigm inside which artifacts are developed. Artifacts must both be relevant to the real-world problem and must be rigorous in terms of quality. As a case in point, the development of a neutron monitor at the North-West University is put forward in this paper.

The paper commences with background on neutron monitor equipment, followed by a sequential report on research projects aimed at delivering a neutron monitor as part of a larger programme. The value of combining an initial risk analysis with structured DSR research is shown and the successes of such a combined effort discussed at the end of the paper.

II. BACKGROUND

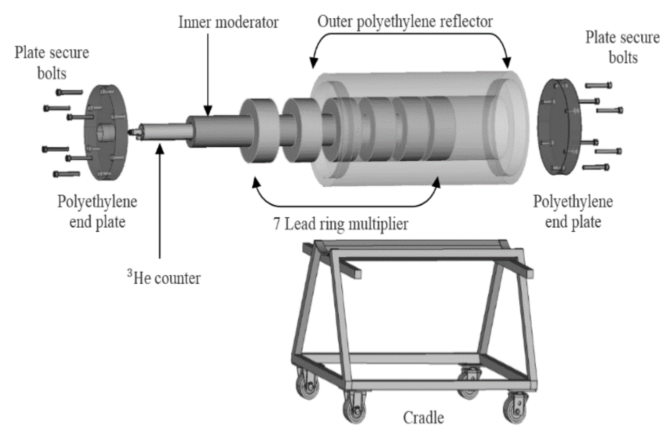

Figure 1 Elements of a neutron monitor counter tube [11].

Neutron monitors are used to measure cosmic ray variations through earth's atmosphere. A key component of a neutron monitor is a proportional counter tube that counts low energy evaporation neutrons generated from collisions between cosmic ray flux (fast neutrons) and atomic nuclei in a producer element made of lead (Pb). After energy conversion and moderation, around 6% of neutrons are effectively converted into charge pulses by proportional counter tubes. Neutron counts serve as an indication of cosmic ray intensity at a given point in time [11].

Following the proportional counter tube, signal conditioning is done by means of a specialized pre-amplifier, after which a discriminator provides digital pulses for each neutron interaction that produced low energy radiation. Pulses are then counted, stored and made available for further analyses. Around a neutron monitor are facilities, personnel, software systems and other system aspects such as logistics, informatics and research interests that must all be taken into consideration.

In order to develop a neutron monitor at the North-West University (in South Africa) for real-world application, it was necessary to combine research and development in a series of R&D projects, starting with a road map as done by Minnie [8], followed by directed research as done by Strachan [9], Fuchs [10], and Nel [11]. The end product was shaped through the research projects to resemble the initial product functionally, but differed in physical form after reflection done during research.

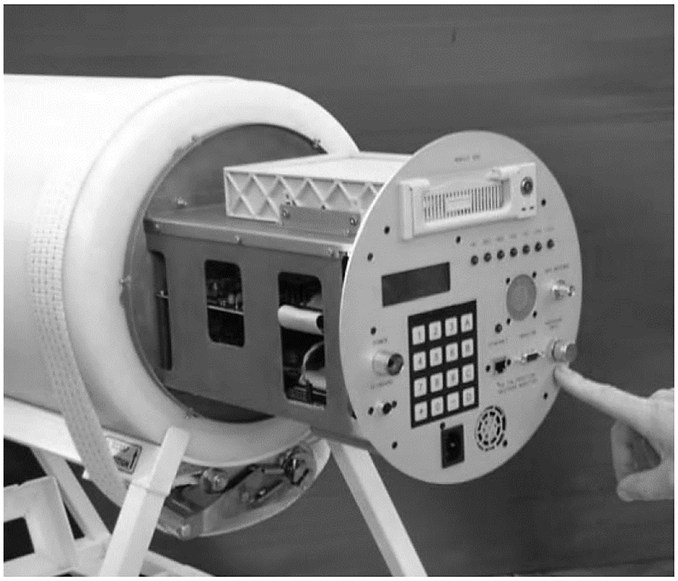

Figure 2 Neutron monitor as in use in 2003 [10].

The research projects were conducted as a collaborative effort between the Faculty of Natural Sciences and the Faculty of Engineering, with the author of this paper as main study leader and engineering manager of development. Subject matter expertise on neutron counter principles was provided by CSR, while the School for Electrical, Electronic and Computer Engineering (EERI) provided expertise on electronic product development and design. The initial road map was used to align both faculties on the research project, to good effect.

III. ROAD MAP BASED ON RISK ANALYSIS

A. *A road map based on risk analysis*

Minnie [8] performed research on the *as is* status of an outdated neutron monitor system as a first research project. In this project, the use of students in research and development projects was highlighted as a risk as both business continuity and technical quality depended on inexperienced students as artifact developers. Development of a road map was done in this project to reduce technical risk and ensure sustainability of the neutron monitoring project at the North-West University's (NWU) Centre for Space Research (CSR). The NWU owns 4 of the 10 neutron monitors in the Southern Hemisphere, and being custodians of these monitors, the NWU accepted responsibility for upgrading and maintaining these monitors located in very remote areas, including Tsumeb in Namibia, Hermanus in South Africa, and SANAE in Antarctica.

The road map was developed by first analysing the *as is* system (a system in the proper sense, including facilities, logistics, people, equipment etc.). From analyses, an FMECA was conducted to identify risk of failure based on equipment age, criticality, and other factors that affect reliability. The main functions of the neutron monitor were first identified:

- Count neutrons using a proportional tube;
- Measure environmental variables;
- Record time and geographical information;
- Measure equipment health status;
- Check monitor operations;
- Maintain monitoring station sub-systems;
- Store neutron monitor data;
- Edit neutron monitor data;
- Publish edited monitor data.

From these functions, resource and interfaces allocations were done to identify critical resources and interfaces that are shared by system-critical functions. These were analysed in a risk identification and mitigation process using the well-known Failure mode, effects, and criticality analysis (FMECA) [12]. A highly detailed FMECA was done by considering failures of all resources in both a functional and piece-part manner to ensure all failures are accounted for.

Following the FMECA effort, a risk analysis was done to ensure a baseline was created for *as is* risk, from which mitigations were put in place. High risk system elements were identified to be addressed in further R&D projects at the CSR. In addition to a series of maintenance, procedural and training mitigations, it followed that a new charge-sensitive pulse amplifier had to be designed, as well as development of a new monitoring and control sub-system employs modern software and hardware to implement complex functions. As a result of the risk analysis, three projects were initiated: (i) synthesis and evaluation of a charge-sensitive amplifier for neutron monitors [9] and (ii) synthesis and design of a smaller monitoring and control system for a neutron monitor [10], and finally (iii) proof of concept for a new monitor to be used at highly remote locations in extreme environments [11]. These are discussed in the following sections.

In all the research projects discussed below, DSR was used to define the R&D paradigm, where each real-world problem was: (i) abstracted and requirements compiled, (ii) the problem researched, (iii) a solution designed based on rigorous, grounded theory, (iv) physically implemented (constructed), (v) the solution verified by means of testing, and (vi) integration of the design artifact into the real-world system after final validation. Throughout, a theoretical knowledge base was updated with design data, which will allow new researchers to understand the rationale behind design choices, refer to baselined designs, and utilize designs as building blocks in more complex systems.

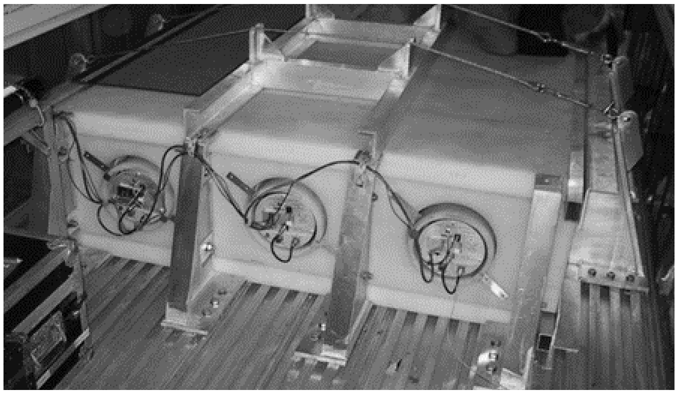

Figure 3 Proportional counter tubes with amplifiers [10].

B. Charge amplifier design

The first research project following the road map, was to address the risk of an underperforming pulse amplifier. Strachan conducted R&D in conjunction with the CSR [9]. The project is summarized as follows:

1. Main objective: Design an amplifier that produces pulses with pulse heights proportional to the amount of charge present on a counter tube's detection wire;
2. Requirements elicitation: R&D requirements were elicited from experts and design goals defined in line with both academic and real-world expectations. In this case, design requirements included (i) design for linearity and specified sensitivity, (ii) electrical interface characteristics to match equipment characteristics, (iii) noise levels had to be acceptable, (iv) transfer characteristics in the form of rise / decay times, dynamic range, and gain had to meet specification, (v) environmental requirements had to be met, and (vi) physical form had to fit existing equipment characteristics, and finally (vii) a specified pulse height density distribution was required;
3. Research and design: The amplifier design was based on well-grounded, fundamental transistor amplifier theory and design principles. The design used a high-impedance dual-FET integrating feedback design as input stage and common emitter BJT transistors as low-impedance output drivers. Simulations were run to characterise the circuit's performance and verified against requirements – hence, grounded theory was used in design;
4. Implementation: The amplifier circuit design was physically realized on a printed circuit board that adhered to the form-factor requirements of the proportional counter tube;
5. Testing / verification: Spice simulations were used to verify aspects such as component variability (using a Monte Carlo analysis) and temperature sensitivity. Experiments were formally set up for verification testing of linearity and pulse height distribution, which had to be verified using the physical artifact (as from CSR requirements).

The physical artifact represented an amplifier that addressed all requirements as elicited from the real world. Theory from the design includes a verified circuit design that may be used in following designs. It is evident that, in the process of applying DSR, both the real and theoretical worlds gained from this research. Without DSR, the design would probably have been realized, but meeting requirements in a rigorous way was ensured by using the balance between theory and practice provided by the DSR paradigm. Future researchers will understand *why* design decisions were made, and the importance of specific design characteristics. As a result, continuity was provided in the form of a comprehensive thesis document as a baseline.

C. Neutron monitor production model development

Concurrent to the amplifier design, a new design for a neutron monitoring and control unit was done in a second R&D project. A unit was to be developed, called an MNM-DAS (mini neutron monitor data acquisition system) by Fuchs [10]. A summary of the project is provided below:

1. Main objective: Design and realize a neutron monitoring and control unit (hardware and firmware) for installation in remote areas;
2. Requirements elicitation: Design requirements included the following high level functional requirements:
    a. Record cosmic-ray activity;
    b. Record environmental variables;
    c. Provide recorded data;
    d. Perform self-diagnostics.

From the high level requirements, lower level functional requirements were derived specifically for the MNM-DAS:

a. Do pulse counting;
b. Generate high voltage for a counter tube;
c. Synchronise system time;
d. Record atmospheric pressure;
e. Record temperature;
f. Record GPS location of the system;
g. Save data on an FTP server;
h. Provide a data backup system;
i. Perform self diagnostics;
j. Allow for human interaction / diagnostics.

Additional requirements included performance requirements (not listed here for the sake of brevity) and physical requirements to define the form factor of the realized unit.

3. Research and design: A Systems Engineering (SE) approach was followed for the preliminary and detail designs of the MNM-DAS [1,2]. Embedding SE in the DSR process supported: abstraction of physical entities in the form of models; formal requirements management; verification and validation; and change management. The concept had already been defined in the outdated neutron monitor recorders, hence there was no need for a new concept design. However, a full functional analysis of the original system did not exist, and was done in order to provide an abstracted system for research purposes. This provided a mapping of system behaviour and architecture. Research

was further conducted on all aspects of electronic design relevant to the project, product development for remote operation and logistic support, and on technologies that were considered in trade-off studies. The design followed an ADM (advanced development model) and EDM (engineering development model) path to result in a production prototype;

4. Implementation: The actual model was implemented with full functionality as outlined in the requirements above. An exploratory development model was not constructed in hardware and consisted of loose-standing functional modules that were constructed and tested individually. The ADM was a fully functional model that represented the final product in form, but was not product-hardened. The EDM (which also turned into a production model) was product-hardened through testing and supported limited production for use in all 4 monitoring stations;

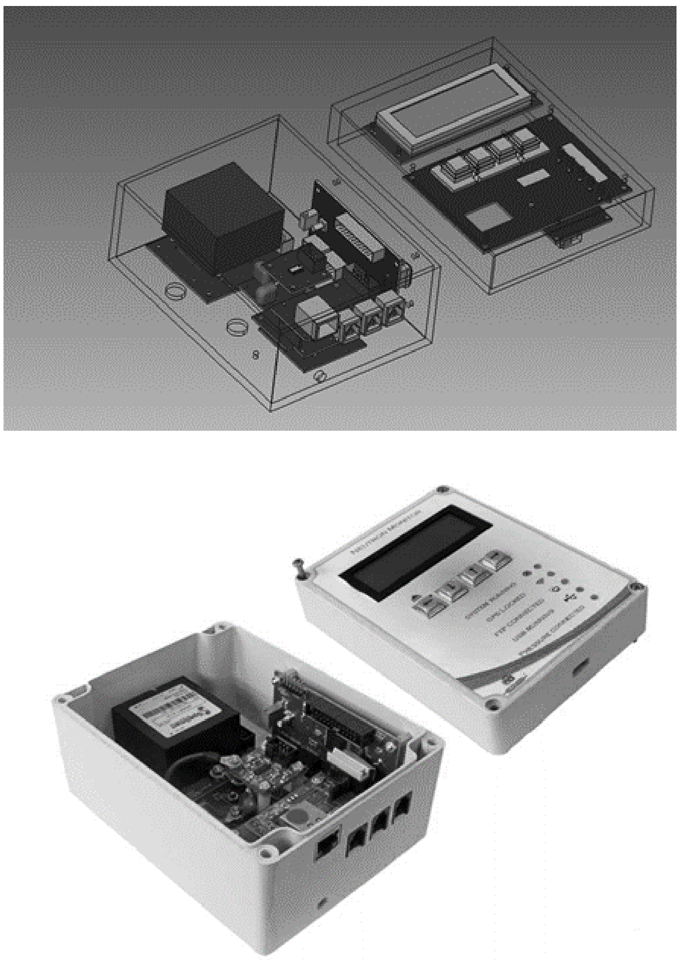

Figure 4 Engineering Development Model in production [10].

5. Testing / verification: Testing of the MNM-DAS was done by means of function tests to demonstrate capability, with experimental testing done where required. Performance tests were conducted on functions such as temperature and pressure measurement, pulse conditioning and high voltage variability, as well as tests on communication performance and fault detection. Overall, the robustness of the MNM-DAS was demonstrated in a product-hardened production unit.

The physical artifact is a physical unit that was installed in all four monitoring sites. A picture of the MNM-DAS as it was realized is shown in Figure 4. With DSR, it was possible to perform a theoretical abstraction of the original neutron monitor for future reference, as the design was added to the knowledge base. Design decisions were documented for future reference and captured in a thesis document as a baseline.

Figure 5 MNM-DAS installation at SANAE in Antarctica [10].

D. Autonomous neutron monitor

Following the successful development of the MNM-DAS, the need for a neutron monitor to be used at high altitudes was defined. High altitude measurements provide an increased counting rate, which is of interest to the monitoring community as a network of 40 units could potentially be replaced. The success of the recently developed MNM-DAS demonstrated development capability at the NWU and resulted in an R&D project to realize an autonomous neutron monitor that may be transported by air and air-dropped at high altitude locations for autonomous operation (on battery power without a permanent communication link). Nel [11] conducted R&D to develop a concept demonstrator to this effect. The project is summarized as follows:

1. Main objective: Design an autonomous neutron monitor for use in highly remote areas with extreme environmental conditions (-60ºC);

2. Requirements elicitation: R&D requirements were again compiled from real-world inputs. More specifically, in addition to the functional of the Fuchs [] design, the following requirements had to be met, namely to (i) operate in locations with a temperature range of -60 ºC and 30 ºC, (ii) provide adequate ingress protection for this application, (iii) operate autonomously for a period of 1 year, (iv) address logistic requirements (physical size, weight, and shock resistance);

3. Research and design: An abstraction was made of the design and physical elements and functions modelled. Research and design challenges were identified and listed for in-depth research, after which a systematic process of technology evaluation and design alternatives was followed. Heat compensation, electrical storage and low power design principles were applied and analyses techniques were applied to address the extremely low (-60 ºC) temperature requirement. Simulations provided valuable information on performance, with temperature modelling being the most challenging as trade-offs had to be conducted to find a balance mechanical configuration and heat transfer;

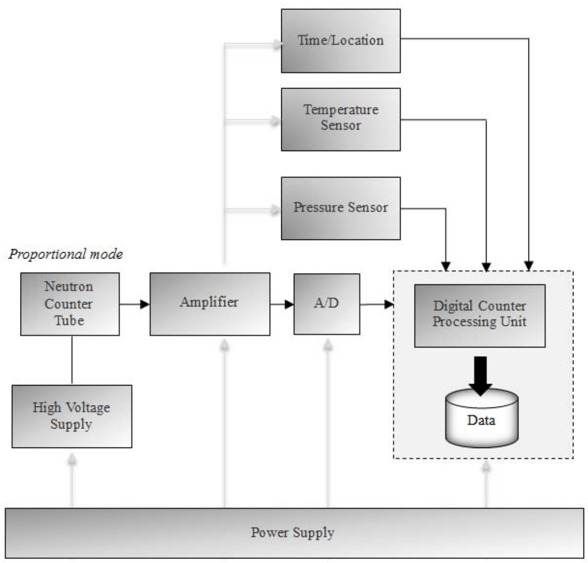

Figure 6 Functional abstraction of a neutron monitor [11].

4. Implementation: A fully functional concept demonstrator of the data acquisition unit was constructed. Due to limited funds, the outer (environmental) enclosure could not be physically constructed, but was thoroughly simulated using a concept enclosure design and thermal energizer for heat control. The data acquisition unit was used for physical testing;

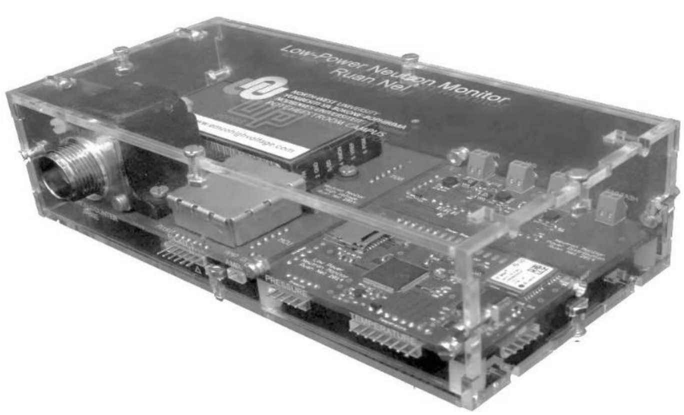

Figure 7 Concept demonstrator of the data acquisition unit [11].

5. Testing / verification: From first principles, thermal modelling was used to verify temperatures at the data acquisition unit, which is the most sensitive to low temperatures. Functional capability was demonstrated, and task performance verified by means of measurements in a controlled environment. Power consumption was measured using a micropower measurement setup, also in a controlled environment. Finally, operation of the data acquisition unit at -70 ºC was demonstrated to show that the unit will withstand extreme temperatures, but as the unit will be thermally insulated and heat controlled, this test was for worst-case conditions only.

The physical artifact in this instance was the data acquisition unit. Instead of doing a straight-forward design, it was required to do a design for extreme environmental conditions and autonomous operation simultaneously. Thermal modelling provided a design for a mechanical enclosure containing a thermal energizer, but the balance between heat control and power consumption had to be met – this was done using low power design constrained by a defined power budget. The research was documented in a thesis document for future reference as part of the knowledge base.

IV. Reflection on Lessons Learned

The challenge of conducting effective, applied research and development in an academic institution is significant. Lessons learned from the collaboration between Faculty of Natural Sciences and the Faculty of Engineering are discussed below, and the value of DSR as an R&D paradigm is highlighted:

- Cultures: Two distinctly different cultures were observed, specifically between natural science (CSR) and engineering (EERI). CSR was highly focused on the end goal, namely that of measuring scientific data, while EERI focused on development, that is, how to achieve said goal. The cultures were aligned by defining a common goal, with each entity's role and responsibility made clear at the onset and managed accordingly;
- Road mapping: The value of allocating an initial research project to produce a road map must not be underestimated. This effort aligned different faculties with totally different cultures, informed researchers on context, and created a vision for the overall programme. In mapping the system, a holistic view of the complexity and scope was obtained, and the impact of improvements could be qualified before the project commenced;
- Risk analysis: In the case of delivering an actual artifact, or series of artifacts, a risk analysis ensures focus of research effort, and effective application of limited development funds, particularly in a resource constrained environment such as a university. The risk analysis done in this instance, was based on an FMECA of a total system, showing which system elements required priority attention;
- Systems Engineering: An SE approach was used to manage requirements, to control change, manage verification and validation, and ensure quality of the final artifacts by providing a development process and tools. SE focuses on development as opposed to design, and is an excellent tool set to align DSR-type research projects. For example, "equipment" in the SE context could be mapped directly to

equivalent "artifacts" in DSR projects, "need and requirements" and its management are used in SE to ensure quality, while alignment with the "real world problem" is used in DSR to ensure relevance, where relevance ensures amongst others the "voice of the customer" is heard, which is also a quality characteristic;

- Design Science Research: DSR provided a paradigm inside which SE could provide products (artifacts). The distinction and interaction between theory and practice (DSR) aligns well with the distinction between abstract models and products (SE), although ontologies differ. "Rigour" in DSR basically ensures an artifact is constructed from proven (tested) theory and building blocks, while "verification" in SE ensures requirements align with characteristics through thorough design evaluation and testing – thus achieving a similar goal;
- Communication: Having defined ontologies available (DSR and SE) inside which to align R&D effort was the most valuable instrument for managing communication between faculties and researchers. This allowed focus and combined effort with minimum effort as misalignment was found to be minimal. It must be stated that the road map and risk analysis research project provided initial alignment as it may have been more difficult to achieve such harmony should this not have been done. Thesis documents were easily reviewed and edited by both CSR and EERI with excellent alignment;
- Innovation: The latest development in the form of an autonomous neutron monitor followed from the baseline created in earlier products. Abstractions (functional analyses) that were used as models could be reused from properly documented theses (as meta artifacts from the DSR process) in a Model-Based SE approach. Innovation started when shortfalls were observed from operational systems – hence the need for exposure to real-world challenges when innovating;
- Continuity: Sadly, with the absence of continued input from a lead researcher (Prof Dr Harm Moraal†), the motivation behind the R&D programme significantly decreased. However, his expertise and wisdom were captured and remain in the knowledge base and future R&D projects will still draw from this base. Business continuity currently lies in the thesis documents and salient knowledge present in the CSR.

Collaboration between business units (or faculties) can be made effective by following good best practice principles. The culture differences between faculties can be bridged by defining common goals and using DSR as a means to translate development ontology (SE / engineering language) to an R&D ontology in the form of the DSR paradigm (research language). The clear value of collaborating with developers to achieve applied research goals is demonstrated with the successes achieved in the research projects.

V. AUTHORS AND AFFILIATIONS

Johann Holm (PhD, PrEng) is an associate professor at the School for Electrical, Electronic and Computer Engineering of the North-West University in South Africa. He is a member of IEEE and a member of INCOSE, and is actively involved in research and development, as well as consulting in operations and product development.

Harm Moraal† (1947 - 2015) did not directly contribute to writing this paper, sadly due to his untimely passing, but his tremendous effort and guidance are acknowledged here. He contributed as a subject matter expert on cosmic radiation, as well as on obtaining funding and being the driving force behind the research projects.

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