Generative Design of soft-armour

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Abstract. Computational models exist to quantify the performance of personal ballistic armour, where ‘performance’ refers to a variety of aspects of personal armour such as ballistic performance or human performance. Balancing the various aspects of performance is (and has always been) the quintessential element in body armour design due to limited load carrying capacity of a person. The Dutch organisation for *Toegepast-Natuurwetenschappelijk Onderzoek* (TNO) has combined these analytical models into a generative design algorithm to aid body armour design optimization by generating an array of potential designs within a given set of constraints. TNO foresees the use of this design tool to explore how body armour design changes with different performance requirements. Alternatively this design tool can be used to explore how a reduction in one aspect of performance requirements affects the other aspects of performance. Generative design of body armour is achieved through a Differential Evolution (DE) algorithm that combines a discretized approach to body armour parametrization with existing computational models of body armour performance. As a proof of concept, TNO implemented a detailed analysis to quantify protective performance, combined with simplified analyses to thermal, mobility and ergonomic constraints. The body armour is parametrized into squares of material that have varying areal density and can be positioned anywhere on the body. This allows (almost) freeform design of body armour. Protective performance is quantified using TNO’s in house developed ICARUS-suite that evaluates four load cases of a fragmenting threat. The simplified approach to thermal, mobility and ergonomic constraints are constructed by assigning penalties to locations on the body where armour is placed. The algorithm evolves a group of designs over the course of a fixed number of generations. The result is a design that specifies body coverage and areal densities and shows the potential of the tool as a means to integrate and balance various aspects of body armour performance. This paper documents the development of the design tool and the various considerations that come into play when combining existing analytical tools in a generative algorithm.

THE PURPOSE OF GENERATIVE DESIGN TOOLS FOR PPE ACQUISITION SECTION

The Dutch MoD operates in a multitude of environments that vary in both climatic conditions and threats. Personal Protective Equipment (PPE), such as body armour, can be further optimized to maximize a soldier’s performance and survivability when it is specialized to different environments (and soldier’s tasks). TNO does not design PPE products nor does TNO do fabrication. What TNO does do is to support the Dutch ministry of defence in her quest to provide the men and women of the Dutch army with the protection that best suits the goals they are trying to achieve. TNO has a rich history (e.g. [1, 2, 3]) in the analysis and model development of soldier protection and soldier performance and we strive to combine this knowledge in a novel application to help the Dutch MoD in defining requirements for future soldier clothing and equipment.

The soldier system is human based, meaning that it inherits the human strengths, vulnerabilities, abilities and limits. The need to protect this valuable system is clear, as is the notion that any additional equipment burdens the soldier and its performance. However, quantifying this balance is a complex undertaking and has been a subject of ongoing research at TNO.

TNO is investing in the development of computer aided generative design tools based on machine learning. The purpose of this development path is to provide an optimization platform in which TNO’s detailed performance models can be implemented, resulting in system optimization based on detailed submodels. A generative design tool can generate and evaluate designs and in this way autonomously explore the design space, a process that otherwise would have to be done manually. By exploring the design space and its resulting designs new insights can be gained to improve specification of system requirements for future systems.

This paper describes the optimization platform and the integration of different performance contributions. This proof-of-concept implements the Differential Evolution (DE) [4] optimization algorithm and TNO’s Integrated Casualty Reduction Simulation (ICARUS) [5] tool, which scopes the application to soft-armour PPE against fragmenting threats.

MODEL DEVELOPMENT

Differential evolution

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This generative design approach implements DE [4], an evolutionary type optimization algorithm. An evolutionary algorithm evolves a population consisting of individuals. The optimization loop (Figure 1) uses a parametrised design created by the DE. That design is sent to a submodel for evaluation to calculate the fitness of this design (i.e. the performance of the design). In the next generation parameters of random individuals (dubbed the parents) are combined (following the DE algorithm) and will evolve if the fitness of the new 'child' exceeds the fitness of the parents. Organized in a loop with a set number of generations, this mechanism drives the evolution that should result in increasingly better performing designs (see Figure 1). In essence this platform is an automated trial-and-error algorithm that autonomously that generates and evaluates possible designs.

TNO's implementation of the ICARUS in the DE algorithm is presented in brief in section 2.2. The armour parametrisation used in the DE is described in section 2.3. The implemented contributions to the fitness calculation are presented in chapter 3

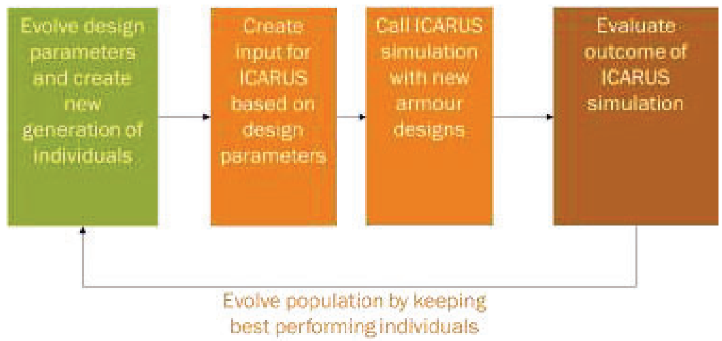

Figure 123 Implementation of ICARUS in the DE optimization loop

Evolutionary type algorithms require that all underlying submodels are evaluated for each individual in every generation. Hence, they are inherently slower than for example gradient based optimization techniques [6]. However, in the unknown design space for complex evolutionary algorithms they have the advantage that they are able to overcome local optima and don't require gradient information that is often not available when integrating existing simulation tools in optimization sequences.

Implementation of ICARUS in DE

ICARUS is a human vulnerability simulation tool that predicts the injury severity due to a fragmenting threat. This is achieved by (see **Figure 124**):

(1) modelling the fragment throw, ballistic trajectory and impact on the person
(2) modelling interaction with fragment protection using the Cunniff model [7]
(3) modelling penetration and retardation of fragments using ComputerMan [8]
(4) modelling injury severity using the Abbreviated Injury Scale (AIS) [9]

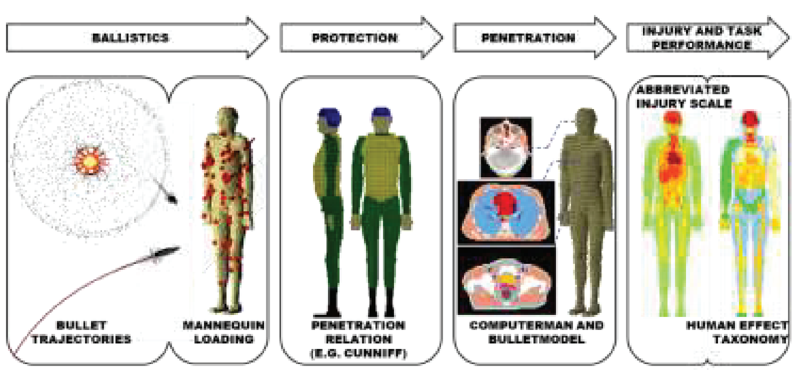

Figure 124 . Brief overview of main ICARUS modules to perform consequence analyses

Traditionally ICARUS has been employed in a forward manner where it is used to analyse the vulnerability of given PPE designs. By enabling automated design of PPE and quantifying the vulnerability in a single metric the generative design loop can be closed, resulting in an automated system. The parametrised PPE design used in this demonstrator is described in section 0 and the evaluation procedure is described in section 0.

Armour parameterisation

The parametrised PPE must be compatible with the input format that is used in ICARUS and the underlying ComputerMan model. In ICARUS protection is included by calculating the velocity reduction of impacting fragments using the Cunniff model [7]. The area covered by protection is defined by selecting which voxels (the elementary building blocks of ComputerMan) are covered by protection.

Figure 125 shows all the voxels related to the outer skin of ComputerMan (front and back) folded out on a flat surface. This "skin projection view" is conveniently used to define which skin voxels are covered by protection by defining squares that encompass the voxels that are covered by protection.

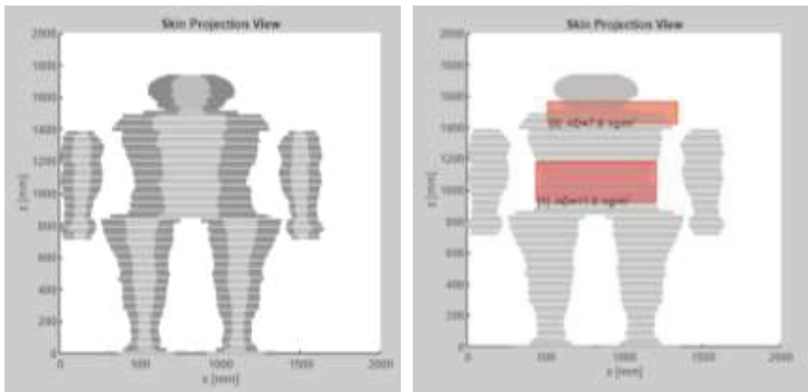

Figure 125. [left] Skin projection view identifying front (light grey) and back (dark grey). [right] Skin projection view with 2 armour squares generated by the DE algorithm. All voxels within the armour squares are covered by PPE.

Each armour square has 5 degrees of freedom: x-position, z-position, height, width and areal density. Currently only a single material is supported, which is the Kevlar KM2 material (see [7] for coefficients for the Cunniff model). Furthermore, the armour squares are restricted to the thorax region.

The DE uses a fixed number of armour squares and varies their degrees of freedom. **Figure 126** shows 4 armour squares, roughly representing a conventional soft-armour insert in an 'up-side-down-T' configuration. Armour squares can move and resize freely, which means that armour squares may result in a disjointed PPE design, or they may overlap. When overlap occurs, the areal density is combined and accumulated (i.e. it is treated as single thick protection, rather than multiple individual layers).

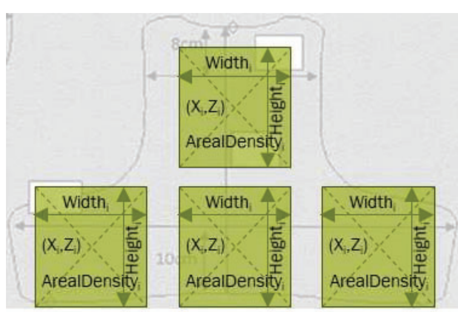

Figure 126 . Example with 4 armour squares

PERFORMANCE ASSESSMENT

Threat definition

ICARUS models injury due to a fragmenting threat, where each fragment is individually simulated and variations in the fragment throw are stochastically drawn. This discrete approach to simulation

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potentially leads to, in an optimization loop, solutions that are optimized specifically to the used loading. To prevent this over-optimization, a variety of loading scenario's must be included in the simulations.

A generic 81mm mortar was selected that is placed at 4 orientations around ComputerMan (see **Figure 127**). Each position is simulated 5 times to obtain a spread in the loading that prevents over-optimization. Hence a total of 20 load cases are considered that are assumed to generate a representative loading.

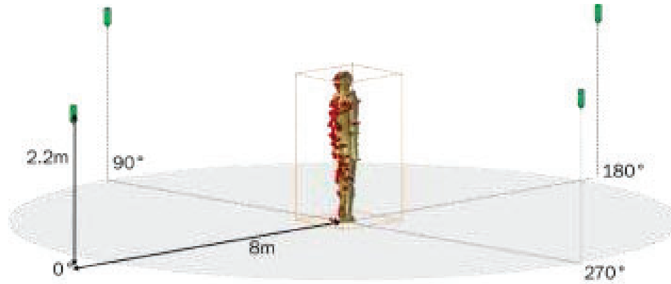

Figure 127 **.** Loading scenario for PPE optimization

Fitness function

The fitness (or performance) of a PPE design quantifies the outcome of a simulation (in this case ICARUS) in a single value. This fitness value follows 2 important guidelines:

(1) The optimization algorithm minimizes the fitness, thus a lower score must correspond to a better performing PPE design
(2) The fitness value must be normalized on a scale from -1 to 0, where -1 corresponds to the (best) upper limit of the achievable performance and 0 corresponds to the (worst) lower limit of the achievable performance

For the protection performance, the fitness is derived from the ability to reduce injury above a specified threshold. In example shown in **Figure 128**, the selected criteria is AIS>=5. The example shows that the PPE design realizes a reduction from 143 to 67 impacts (resulting in AIS>=5). The corresponding normalised fitness score is then -67/143=-0.469. If all fragments were to be stopped by a PPE the best score of 0/143=0 is achieved. If none of the fragments were to be stopped by a PPE the worst score of -143/143=-1 is achieved.

Criteria: AIS>=5	Unprotected	Protected
Nr. hits total	498	498
Nr. hits (AIS>=5)	143	67
Fitness score	-	-67/143 = -0.469

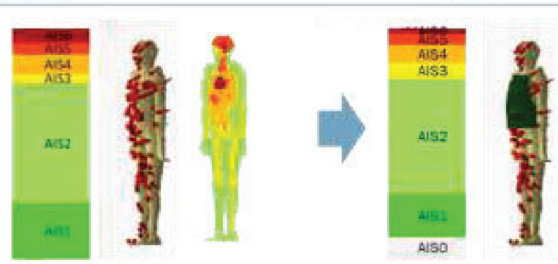

Figure 128. Example of fitness calculation for injury reduction

This fitness calculation is implemented such that the user can specify an injury criterion. In future versions, that are currently under development, we are developing a scoring system that takes injury reduction at all AIS levels into account.

Other performance contributors

An unrestricted optimization algorithm that is driven only by minimization of injury will always result in a design that will cover the complete body with the best (and usually heaviest) protection possible. In

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the future each contribution to the overall fitness will, like is the case with ICARUS simulation, come from detailed submodel analyses. In the presented proof-of-concept that interplay of detailed submodels is not yet available and a maximum mass for the PPE is prescribed.

Other contributions to performance have been included , but in a heavily simplified manner by applying for a weighted area approach. For example influence of thermophysiology is approximated by assigning more severe penalty values to areas that sweat more intensely [10] (see **Figure 129**), thereby giving the algorithm the incentive to avoid those areas.

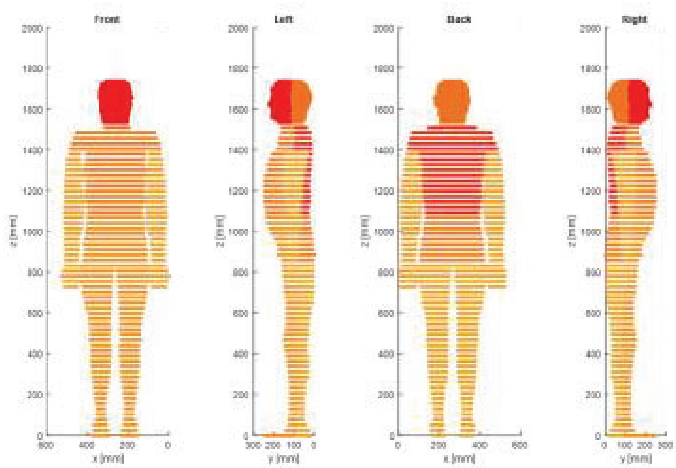

Figure 129. Penalty values assigned to sweat regions. Based on [10]

In addition to injury, the following performance contributions are implemented (as stated in a highly simplified manner): thermophysiology, thermosensitivity, ergonomics, stability.

Although the fitness score from each performance contributor is normalised there is subjectivity in the selection and combination of performance contributions. Using the normalised score per contributor implicitly assumes that each performance is weighted equally and is thus equally important. Secondly, for example thermophysiology and thermosensitivity address related (but not identical) performance contributions. By including both of them in the overall fitness, versus only 1 injury contributor, the optimization algorithm implicitly weighs thermal effects 2x as important. In the current implementation these considerations were addressed by manually assigning weighting factors to the contributors. Manual weighting factors are not preferred and in the next iteration of this optimisation algorithm a procedure is sought to objectively derive weighting factors.

RESULTS

A demonstrator was run, where the DE algorithm is allowed to evolve 8 armour squares to an optimal configuration, where the weighting factors were chosen to emphasize results from the vulnerability analysis. A population of 25 individuals are evolved over approximately 2000 generations , after which no more significant variations in the design are observed. The start, intermediate and final solutions are presented in **Figure 130**.

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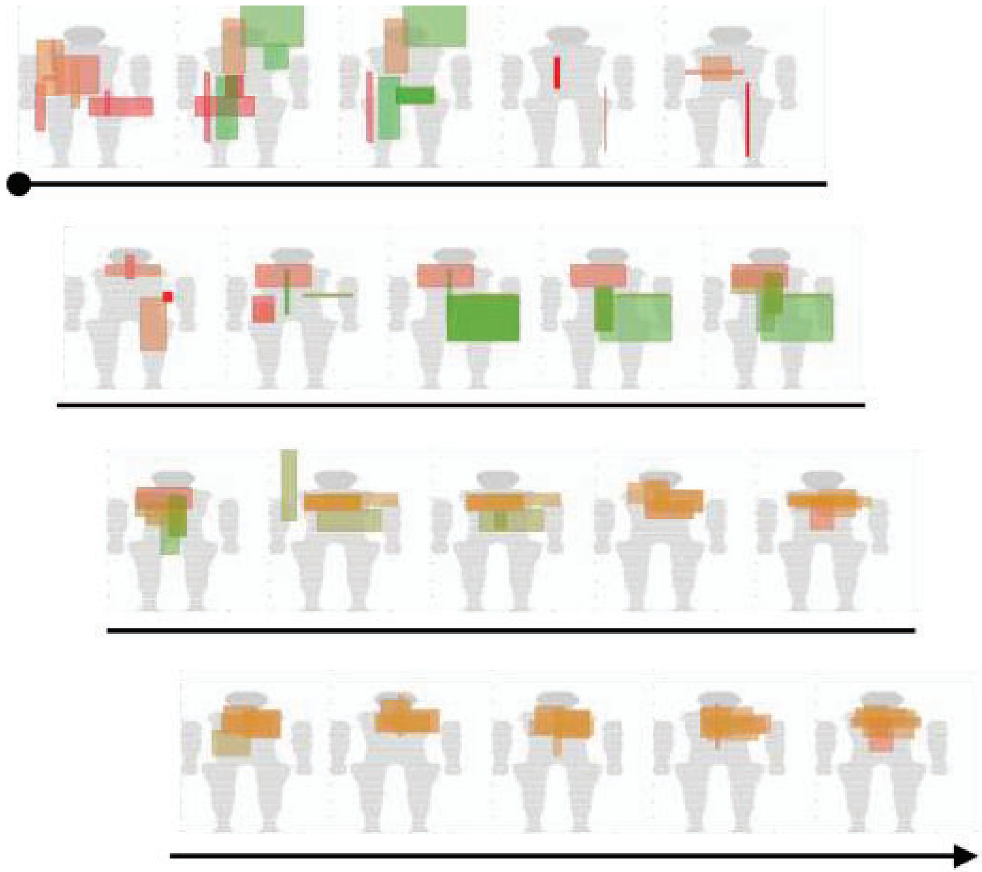

Figure 130 . Example result with 8 armour squares presented on the skin projection view. Colours represent areal density and range from green (low) to red (high)

The resulting PPE design has evolved to protect the upper thorax where most of the severe injuries (AIS>=5) can be found. Note that contrary to conventional up-side-down-T configuration, the found design more closely resembles a 'normal-T' configuration. This result can be explained because it maximizes protection of the requested AIS>=5 areas and is not rewarded for protection AIS4 zones (such as can be found in the abdomen. The horizontal upper-bar of the 'T' aims to protect the heart region (from impacts from all orientations). The vertical bar of the 'T' aims to protect the heart, aorta and nerves in the spinal region from impacts.

This demonstrates that the DE algorithm, coupled with ICARUS, can be used to generate logical designs that are in line with expectations. The design resulting from this exercise inspires the idea that in a high risk scenario, where high mobility is desired and only the most vital areas of the body are asked to be protected, an unconventional 'normal-T' design should be considered as an alternative.

CONCLUSION & FUTURE DEVELOPMENTS

In this paper the initial development of computer aided generative design algorithm is presented that can autonomously evolve PPE design. The underlying optimization algorithm is a differential evolution algorithm, coupled with TNO's ICARUS vulnerability assessment tool. The resulting tool shows that a outcome that is in line with expectations, but that still requires an subjective assessment of weighting factors

This development marks an important step in TNO's suite of tools, because it demonstrates that existing (analysis oriented) tools can be employed in an generative design algorithm. However, this generative design tool is not a step for TNO towards PPE design, but is a step to improve the ability to translate operational requirements to technical requirements for PPE. For example different PPE designs could be generated that prioritise different performance contributions. The outcomes will give insight in the dimensions and specifications that should be placed on PPE. We foresee application of this generative design tool early in the procurement phase, when defining the programme of requirements for new PPE.

The current generative design algorithm includes only protection against and injury due to fragment threat. The next iteration, which is currently under development, will introduce a number of new features: (1) introduce the ability to include different materials. (2) Expand the current implementation with TNO's Predicted Heat Strain (PHS) [11] model that models thermal strain due to physical activity and PPE. (3) Provide an procedure to objectively derive weighting factors. Here, the latter is of great importance, because it will allow for a more objective balance between the different performance contributions. The inclusion of PHS and ICARUS allows us to attempt to impose operational requirements on PPE (as opposed to artificial requirements such as weight) to see what designs are generated.

Despite all the so-called "intelligence" of generative design loops the results must always be carefully interpreted. As is the case for all simulations, the outcome is only as good as the underlying models and input. For example, at this moment the generative design loop does not consider aspects such as manufacturability or comfort, both of which are essential drivers of PPE design. Despite that shortcoming, explorations with this generative design tool will alleviate much of the trial-and-error effort that is otherwise manually performed and through its results it provides TNO and the MoD with insights into realistic and sensible technical requirements to impose on future PPE systems.

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