Proposal
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Fast physics-based fracture for visual effects

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End user parties:	3D content creation sector Weta Digital Limited		

Executive Summary

Imagine you are the director of a feature film. You want to depict a scene involving a 17th century ship in a storm. The main mast creaks, bends, and finally breaks into splinters. Fifteen years ago you would have used scaled-down physical models for the scene. Today you are much more likely to use computer animation and digital visual effects. What has changed over these fifteen years is the degree of physical realism that computer simulations are able to deliver. But if you look closely at the splinters of a simulated mast you will notice that the fragments do not look as realistic as the surrounding water. Present day technology is not fast enough for the simulation of realistic fractures in complex scenarios.

How fast can we simulate real-time fracture in a multi-material context without sacrificing the underlying physics? Can we achieve real-time interactivity? Can we use high-end desktop computers for this purpose? In this programme we propose a novel hybrid of state-of-the-art physics-based fracture simulation techniques and model size reduction methods to address these questions. This hybrid method has the potential to reduce the compute time of complex scenarios from days to hours. For real-time interactive simulations needed by pre-visualization artists early in the process we propose a rule based approach; the rules will be extracted from detailed calculations. The fracture simulation techniques will be designed so that they integrate seamlessly into a software framework for the simulation of interacting deformable solids, liquids, and rigid bodies. Multi-processor desktop computers will be the target hardware.

Phase 1 of the programme is targeted towards applications in visual effects and is driven by the requirements of the digital content industry, in particular Weta Digital Ltd (Weta). The refrain in this industry is “faster is better,” while retaining plausibility. Therefore, the key requirements are high simulation speed and physical realism.

The visual effects industry in New Zealand is driven by a highly competitive world market in motion pictures and computer gaming, estimated to grow to US$100 billion by 2016. An increased share of this market can only be achieved through innovative effects and unique capabilities. Our research programme is designed to augment concurrent research at Weta intended to create a set of unique tools for their visual effects simulation teams. These new capabilities will help Weta retain its competitive edge in the feature film market and grow its market share significantly over the next five years. The programme will also train students in the computational engineering and software development skills that will be needed by the industry as it grows, complementing the planned computer graphics programme at Victoria University. Dr. Andreas Soderstrom (Weta) is the key person who will help transfer our research results to Weta.

While Phase 1 of the programme has a feature film visual effects focus, the niche fracture simulation technology developed in this programme is applicable directly to the rapidly growing computer gaming software industry in New Zealand. Additional spill-over effects in the form of virtual surgery training tools for the medical implant industry have the potential of increasing New Zealand's share of the world medical device market. Excessive compute time is also a barrier to the widespread adoption of computational fracture analysis in engineering design. The techniques developed in this programme have the potential to seed new New Zealand engineering analysis companies that can access the global market by providing the unique capability for rapidly evaluating when a design will fail.

The research team is led by Dr. Biswajit Banerjee (IRL) who is an expert on computational fracture and parallel simulation software development. Dr. Bryan Smith (IRL) is an emerging scientist with expertise in model simplification and fluid-solid interaction. Dr. Kumar Mithraratne (University of Auckland) is an expert on soft materials, computational mechanics, and rigid body dynamics. Dr. Geoff Willmott (IRL) is a world leader in high speed photography of fractures. Prof. Florin Bobaru (University of Nebraska) is a leading expert on the peridynamics method for fracture simulation. Two post-graduate students will assist the leaders of the project. A group of early tertiary students from the Manukau Institute of Technology led by Mr. Lee Taituha will work closely with the team on experiments, parallel simulations, and visualizations aimed at contributing indirectly to Vision Matauranga.

Executive Summary

Public statement

Computer simulations of the motion and fracture of physical objects are used in motion picture visual effects, computer games, virtual-reality training, and engineering design. Engineering simulations have to predict physical behaviour as accurately as possible. A single dynamic simulation involving a large number of fractures can take days to complete. Visual effects, on the other hand, require physically plausible simulations that are not necessarily accurate but can be computed rapidly.

This research programme will develop numerical techniques, material models, and software tools for the fast simulation of fractures in a dynamic setting containing interacting solids and liquids. These tools will be used for the simulation of various types of destructive effects in computer-generated imagery. The main challenge of such simulations is that high-speed computation and physical realism are often mutually exclusive. The aim of this programme is to address the contradictory requirements of speed and realism desired by the visual effects industry. To achieve high simulation speeds, the research programme will explore novel algorithms that take advantage of on-demand problem simplification. Simplified rules for generating realistic fracture geometries will be extracted from massively parallel simulations of fracture processes to further reduce the real-time physics calculations that are necessary for enhanced realism. A group of early tertiary students will work closely with the researchers in performing simulations, visualizing the results, and extracting rules from simulation data.

Smart Ideas

Vision Statement

Computer simulations of physical processes provide a powerful alternative for exploring new engineering designs, complex hazard scenarios, and new scientific theories when experimental approaches are expensive or impractical. Physics-based simulations have also become indispensable for visual effects. Rising transport costs will increasingly make manufactured products from New Zealand less profitable in the world market. Innovative computational simulation tools, know-how, and value-added services will be one way of countering the potential decline in manufacturing competitiveness. This program will augment Weta's suite of simulation tools and enable an estimated NZ$50 million additional export earnings in the visual effects and computer gaming sector by 2018. Surgical training tools for new medical implant designs are envisaged for the medium term. The long-term vision is to apply these tools to rapid engineering design.

Alignment with investment mechanism and sector requirements

Simulations of fracture processes are increasingly being used in digital content creation and engineering analysis. How fast can we simulate fracture in a multi-material scenario while maintaining physical realism? The innovative hybrid of several computational methods that we have proposed for Phase 1 of this Smart Ideas programme is expected to reduce computation time by an order of magnitude over currently available approaches. Our collaboration with Weta Digital will ensure that the programme has a strong focus on applications relevant to the visual effects industry. In Phase 2, the techniques and software tools developed in this programme will be extended so that they can be applied to computer gaming and virtual surgical training applications. The current proposal is for Phase 1 only and the total requested funding amount is NZ$455,000 per annum for two years.

Alignment with assessment criteria

Outcome Benefit to New Zealand

Phase 1 of this programme is aimed towards niche value-added services that leverage physically based digital animation. Major New Zealand companies in this space are Weta Digital (Weta), Sidhe Interactive (Sidhe), and Digipost [1]. Global animation software sales accounted for US$370 million in 2010 and are expected to grow to US$820 million in 2016 [2]. The size of the market for value-added digital animation services is not readily available, but is related to the sizes of the motion picture and computer games industries. The worldwide box office sales of motion pictures grew to US$32 billion in 2010, [3] while the computer games industry was worth US$53 billion in the same year [4]. The revenue earned in 2011 by Weta, Sidhe, and Digipost has been estimated at US$100 million [1]. Growth in this sector is expected to be driven by companies with the capability to develop unique and innovative functionality [4].

The industry partner for this Phase 1 programme is Weta, a Wellington based digital effects service provider to the feature film industry. Simulations are a significant component of Weta's activities and state-of-the-art simulation tools are critical for the company to remain competitive [5]. State-of-the-art tools used in physics-based animation are, for the most part, stand-alone and highly specialized. This programme will develop the next generation of tightly integrated multi-purpose tools that provide improved realism while retaining high simulation speeds. These improvements in simulation technology, along with concurrent in-house developments at Weta, have the potential to increase the size of the US$2.5 billion New Zealand visual effects and computer games sector [6] by more than 2% over the next five years. Continued growth of New Zealand's digital animation sector will require research and development staff that are trained in computational engineering techniques and algorithms, software development, and computer animation [5]. An important outcome of this programme will be the training of students in these increasingly sought after skills.

Implementation Pathway

The main objective of Phase 1 of this programme is the development of fast and innovative techniques for failure and material simulation that can be used for creating visual effects. These techniques will be developed on the Uintah [7] open-source parallel computing software platform. The new software IP developed on this platform will be retained by Industrial Research Limited (IRL). For the research to be of benefit to Weta, these tools have to fit seamlessly into their in-house multi-material simulation software. While software programs will not be directly transferred to Weta, the following will be communicated at regular intervals: the effectiveness and robustness of the computational fracture mechanics and model size reduction algorithms, simplified material models for fracture and deformation, and simplified fracture evolution rules identified from simulations.

Weta has a well-developed process, and dedicated personnel for transferring research knowledge into production tools. Our programme will depend on Weta personnel to implement the new knowledge into their proprietary software. Implementation issues such as mapping discontinuous (fractured) objects to the original source objects and user-interface issues, such as artist control of material parameters, will also be handled by Weta.

The IP landscape in the animation software industry is complex but unhindered by regulatory requirements. The fundamental algorithms used for most simulations are in the public domain. We will take advantage of IRL's and Weta's existing processes to ensure that any technologies we develop have freedom of operation.

In Phase 2, the programme will be expanded to include computer gaming companies such as Stickmen Studios and surgical simulation software users such as Adept Medical and Enztec. The target is the niche market in training software for new medical implant designs [8]. The prototypes developed in Phase 1 will be critical in demonstrating the benefits of physically based tools to companies in these industry sectors.

Research, science, and technology benefits to New Zealand

The primary research question that this programme will address is: "How fast can we simulate nonlinear dynamic fracture in a multi-material context while retaining the underlying physics?" The computational expense of full-physics nonlinear dynamic fracture is a barrier to the widespread use of existing simulation techniques in engineering design and virtual prototyping. The need for speed is even more acute in the visual effects industry than in engineering and, at first glance, the conflicting requirements of speed and physical realism appear impossible to reconcile. We will use a hybrid computational approach for physics-based fracture and automated model size reduction techniques for improved speed. We will also extract fracture evolution from detailed simulations for use in pre-visualization applications where real-time interactive response is needed.

Novelty of idea: The current paradigm in visual effects is based on the use of stand-alone tools. For example, flow is simulated with specialized hydrodynamics software, and waves and froth are then added to the main flow with other specialized tools. Simulations of destructive effects require additional tools that are rarely physics-based. The proposed programme represents an alternative to the classical stand-alone approach used by the visual effects industry. This programme is novel because:

1. It is the first application to visual effects of a unifying computational framework that can simultaneously simulate solids interacting with liquids, dynamic fracture, and multiple solid materials.
2. It is the first attempt to tie together rigid body dynamics, a recently developed theory for the simulation of fracture (peridynamics) [9,10], and a particle-based approach for continuous solids and liquids called the material point method (MPM) [11,12].

Research plan:

Research hypothesis: Challenging scenarios in visual effects and engineering simulations include the splintering of anisotropic materials such as wood, the fracture of layered composites of hard and soft materials, and the tearing and crushing of thin objects such as metal sheets or soft leather [5]. These challenges become more severe when interactions with liquids are involved. Our research hypothesis is that the combination of peridynamics and MPM will deliver the realism needed to address these challenges. We will address the question of speed by taking advantage of parallel computing, model size reduction approaches, and the fact that visual effects do not require the same degree of physical accuracy as engineering.

Research aims: The three research aims of the programme are computational fracture mechanics, model size reduction, and knowledge extraction from detailed simulations. Planned activities are shown in Figure 1 (attached). Computational fracture mechanics includes the development of techniques and material models for the simulation of fracture and experimental validation with high-speed photography of fracture processes. Model size reduction includes rigid body dynamics, homogenization of material properties, and the exploration of rigorous model-order reduction methods. These size reduction methods will feed information directly into fracture mechanics algorithms or indirectly via mode transitions. Manual knowledge extraction from detailed simulations will continue throughout the process and automated projection-based techniques will also be explored.

Rationale for the approach: In the visual effects context, the requirements for a simulation tool for multi-material dynamic fracture are speed and physical realism. However, physical realism and speed are conflicting goals and difficult to achieve simultaneously. One reason for the high cost of simulating dynamic fracture is the fact that continuum mechanics and fracture are fundamentally incompatible. Continuum mechanics approaches require smooth deformations and continuous objects. Fractures involve discontinuous jumps in deformation that have to be addressed using mechanisms such as strong discontinuities or enriched elements [13]. Because these techniques involve a significant amount of bookkeeping, computational time cannot be reduced even if a large number of processors are applied to the problem.

Our approach is to apply a novel hybrid of the material point method (MPM), peridynamics, and parallel computing to reduce the cost of physics-based fracture simulations. MPM [11] is a continuum mechanics approach that uses Lagrangian particles with a background computational grid to solve nonlinear dynamics problems. It allows the simultaneous simulation of solids and fluids, and naturally imposes contact between bodies, making contact detection extremely efficient. Peridynamics [9] is a method that was designed for the simulation of fractures. It does not require smooth deformation gradients. Jumps in deformation can be treated in a natural manner by the stretching and breaking of bonds, so special treatments are not needed for the simulation of failure. These qualities make a combination of these methods ideal for physics-based multi-material dynamic fracture simulation, especially for situations involving solid-liquid interactions.

Early in the production process, visual effects artists desire real-time interactivity with their simulation tools for pre-visualization of scenarios. Simulations later in the process need more detail and are afforded longer simulation times; but "faster is better" [5]. Parallel computing will reduce the computational time needed by the planned fracture mechanics approach. Further increases in speed will be made possible by reducing the problem size. Homogenization techniques will be used to reduce the problem size in space (by reducing the degrees of freedom) and in time (by eliminating high frequency vibrational modes). Just-in-time rigid body dynamics will be used where expensive deformable-body mechanics are irrelevant. However, the above improvements are not sufficient for real-time interaction. This programme will approach the interactivity issue by developing rule-based approaches (heuristics) for the evolution of fractures that can be used for pre-visualization.

Organizational and infrastructural support: Computational infrastructure provided by IRL and the New Zealand eScience Infrastructure (NeSi) will be used extensively in this programme. Experimental infrastructure will be provided by IRL.

Ability to Deliver Research, Science, and Technology Results

Plan for mitigation of technical challenges: There are several technical challenges in the proposed program. Coupling peridynamics to MPM and rigid body dynamics is an unsolved problem and may lead to lack of robustness in the computations. Any issues that arise will be addressed by the collaborations with Prof. Florin Bobaru and Dr. Kumar Mithraratne, both of whom are experts on computational issues. Anisotropic dynamic fracture (such as splintering wood) has not been addressed adequately in computational mechanics and simplified models will have to be developed. The expertise of Prof. John Nairn (University of Oregon) will be used if anisotropic fracture becomes an intractable problem. Nonlinear homogenization of dynamics is a subject of ongoing research and rigorous approaches have not yet been developed. Our initial approach will be to use simplified models for Phase 1 of the project and a collaboration will be established with Prof. Amit Acharya (Carnegie Mellon University) if these models prove inadequate. Extraction of fracture heuristics for complex three-dimensional problems has also not been addressed in the literature and we will focus on extracting heuristics from problems that are nominally two-dimensional.

Milestones and Go/no go points:

1. *Transition between MPM and peridynamics complete by June 2014.* If peridynamics and MPM cannot be coupled in a robust manner, focus will be shifted to improving the speed and robustness of the peridynamics code and material models.
2. *Model size reduction algorithms complete by April 2014*: If the proposed model size reduction methods do not deliver higher speeds, other approaches will be sought.
3. *Heuristics extraction complete by September 2014:* If manual extraction of rules for the evolution of fracture paths proves too complex focus will be shifted to automated methods and the delivery of heuristics will be postponed to Phase 2.

Previous research experience: The research is primarily theoretical and computational and requires personnel with expertise in computational mechanics. A limited amount of experimental work is needed in the form of high-speed photography of fracture events. The lead researcher, Dr. Biswajit Banerjee, has 16 years research experience in theoretical mechanics, numerical methods for nonlinear dynamic simulations (including the material point method), constitutive modelling, and parallel computing. He has project managed to completion several research projects at IRL. Dr. Banerjee also has experience in commercial computational engineering software development and was a key developer of material models for the Uintah massively parallel computing framework as part of the Advanced Simulation and Computing Center (C-SAFE) at the University of Utah [14,15]. Dr. Bryan Smith has 10 years research experience in numerical methods for the simulation of strong discontinuities, statistical techniques, and physics-based model order reduction for turbulence problems. He will contribute to the model size reduction and knowledge extraction aspects of the programme. Dr. Kumar Mithraratne has more than 15 years research experience and possesses expertise in finite element modelling, soft tissue mechanics, and rigid body dynamics. Currently he is leading a 4-year NZD 1.8 million MSI/TechNZ research grant. Dr. Mithraratne will contribute to the development of rigid body dynamics software, mode transition, and simplified material models for soft materials and will be the co-supervisor of two post-graduate students.

Collaborations: Additional planned collaborators include Dr. Geoff Willmott (IRL), Prof. Florin Bobaru (University of Nebraska), Dr. Andreas Soderstrom (Weta), and Mr. Lee Taituha (Manukau Institute of Technology). Dr. Willmott has previously obtained world-first results in high-speed photography [16,17]. Prof. Bobaru is a world-leading expert on peridynamics [18,19] and will contribute to the peridynamics aspects of the Programme. He will also co-supervise a student who will travel to Nebraska. Dr. Soderstrom is experienced in the implementation of MPM into Weta's software framework and will be the key person involved in transferring knowledge developed in this programme to industry. Mr. Lee Taituha will co-supervise early tertiary students who will contribute to experiments, simulations, and knowledge extraction.

Vision Matauranga (VM): While this proposal does not depend on, or leverage, specific Maori knowledge, resources and people for its success, the cultural knowledge of a cohort of Maori students from the Manukau Institute of Technology will be integrated into the experimental and knowledge extraction aspects of the programme, while assisting these students in the development of computational skills.

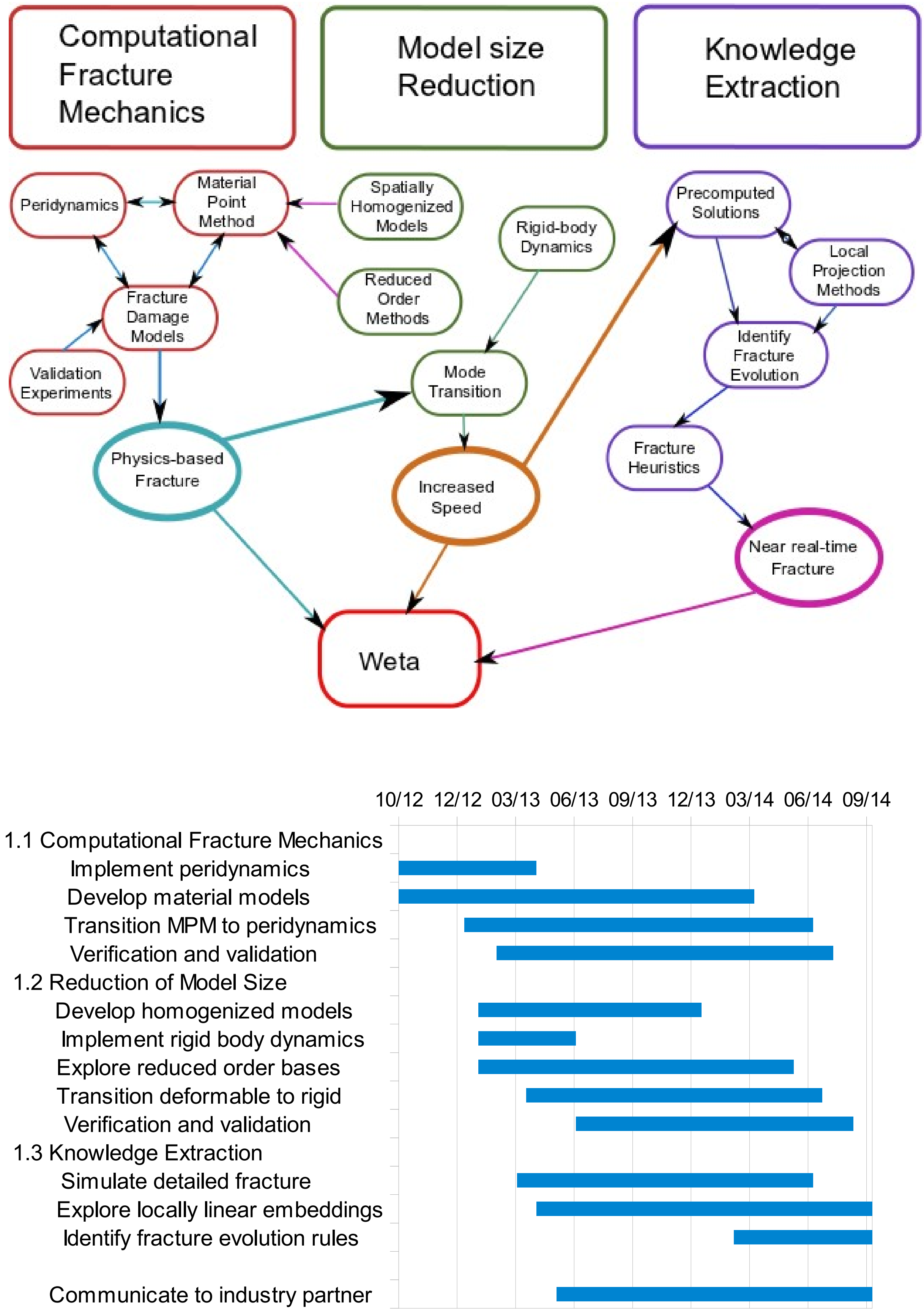

Figure 1. Project map and time-task schedule for research programme.

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Detailed methodology

Background: Dynamic failure modelling and simulation is an active research area in computational mechanics [1]. New physics paradigms such as peridynamics [2,3,4], improved algorithms such as the material point method (MPM) [5,6], and model order reduction [7] are some of the directions in which dynamical fracture simulation is being driven, primarily by the need for fast but accurate tools with minimal problem set-up times. The visual effects and surgical simulation fields are also converging towards greater physical realism while retaining the speed of computation delivered by purely geometric approaches to failure [8,9,10]. The approach proposed in this programme will allow for physically-based simulations of fracture in a software framework that seamlessly integrates the interaction of fluids and solids, does not require extensive searching to determine contact interactions, and performs on-the-fly model order reduction. This hybrid technique has the potential to deliver superior physics for the same computational cost as existing finite element and meshless methods.

The accurate simulation of the initiation of failure and the subsequent growth of multiple cracks before global failure continues to be one of the key challenges in computational engineering. Several techniques, including enriched finite elements (FEM) [11] and cohesive models [12] have been developed over the past 20 years in the context of mesh-based finite element methods. These methods require a significant amount of bookkeeping when dealing with multiple cracks, do not translate well into parallel software codes, and the solutions often fail to converge and are unstable. As a result they are slow and unpredictable and are often avoided even by skilled analysts. If we wish to add the effect of a fluid on a solid undergoing failure, such as a water-filled balloon pricked with a pin, the problem becomes even more involved. Boundary pressures and displacements have to be transferred between the solid and the fluid, and both systems have to achieve force equilibrium at each time step of a simulation [13]. This necessitates small time steps and a slow analysis that may take several hours to days to simulate one second of real time.

While the goal of computational mechanics is fidelity to physical processes and predictability, researchers in the field of visual effects are not similarly constrained. Physical accuracy can be sacrificed if the results are visually plausible, but short turn-around times are critical. Early visual effects treated objects as rigid bodies. Solids and fluids were simulated separately and the results tied together by skilled artists. However, visual effects researchers have found that creating realistic looking scenes can be generated more efficiently by incorporating deformable body physics into their simulations [14]. The tools available today are capable of generating quite realistic looking simulations using a minimum of physics as evidenced by Fracture FX Demolition Software and Dynamica. Solid-fluid simulation within a single framework continues to be a research topic [15] in the visual effects industry and a few companies have developed products that include this feature.

Rationale: Recent developments in computational mechanics have seen an upsurge in mesh-free or particle methods of simulation. MPM is a particle method where the material history is stored on particles while the conservation of momentum is solved on a regular background grid. This method has the advantage that several different materials can be simulated simultaneously. The materials interact via the grid and specialized contact detection algorithms are often not needed. The method has also been used to simulate fluid-structure interaction [16] and fracture and fragmentation [17] with a reasonable degree of success. A separate avenue of research has led to the development of peridynamics which has similarities with molecular dynamics. This method is a significant deviation from standard continuum mechanics in that the stress at a point is computed using the displacements of nearby points rather than local displacement gradients. A feature of this method is that fracture is determined naturally by the breaking of bonds and extra geometrical bookkeeping and complex constitutive relations are not required.

Developments in visual effects research have focused primarily on FEM for modelling deformable solids. Innovative approaches that do not necessarily have any physical basis have been used to model material behaviour. Coupling of fluids and deformable bodies continues to be a research topic [18] and considerable interest has been expressed regarding MPM and other mesh-free methods [19]. Fracture continues to be predominantly geometric, using Voronoi tessellations to determine fragment geometries. However, recent developments in destruction engines have used damage accumulation and finite element splitting to produce realistic looking anisotropic fractures [20]. Current destruction/dynamics simulation engines, such as the open source Bullet plug-in for Maya and the Fracture FX demolition software, use rigid body dynamics for speed. Non-physical Voronoi tessellation is used to generate fracture paths, and collision detection is purely geometric and computationally expensive. These engines are usually stand-alone and can only be used for one purpose, the simulation of failures. Discussions with Weta have indicated that there is a need in the visual effects industry for a unifying framework that can be used for solid-fluid interactions and fracture. The framework should be able to incorporate realistic physics but also produce fast, preferably real-time, simulations of complex scenarios.

The key aim of this research is the achievement of physical realism without sacrificing speed in multi-material failure simulations. MPM can be used for solid-fluid simulations but does not always deliver realistic failure paths. The method can also be expensive because of the need for small time steps in explicit simulations. Peridynamics is ideally suited to handle the failure of materials but is inadequate for fluid-solid interactions in its present state of development. It can also be relatively slow because non-local aspects of the method require a large number of integrations. Therefore, a method is needed that can take advantage of the strengths of both methods but is also computationally fast.

Description of key research: The key components of the proposed research are high-quality computational fracture mechanics for physical realism, model-order reduction for improved speed, and knowledge heuristics extraction for near real-time applications. Verification of models and validation of simulated results with high speed videos of experiments will be an integral part of the research programme.

To achieve physical realism with improved speed in fracture simulations we propose a hybrid method that uses MPM, peridynamics, and rigid body dynamics at various stages of the computation of solid deformation and fracture. Fluids are treated directly with MPM and interaction between solids and fluids is through a background computational grid. The method will be implemented and validated within the Uintah computational framework [21]. Improved computation speeds will require a split of the computational domain into "interesting" and background regions. Rigid body dynamics will be used for parts of the domain that are not interacting with other objects and during periods of time where the grid does not feel any interaction between objects. Once it has been determined that rigid body dynamics is no longer sufficient, MPM will be turned on. The MPM simulation will initially use a real-space renormalization approach for spatial homogenization [22] to reduce the number of degrees of freedom in the system.

When MPM detects that fracture events are imminent, the peridynamic simulation will be activated. This simulation will require the mapping of material models from a continuum mechanics framework to a peridynamic framework [23]. Semi-implicit or implicit algorithms may be needed for large stable time steps in the peridynamic simulation and these will be explored late in the project. A heuristic will be developed that will indicate when a peridynamic calculation is no longer necessary and the simulation will revert back to the MPM, and if possible a rigid dynamics mode. All of these aspects will be simulated in a single computational framework by assigning hierarchical structures to different parts of the computational domain, and material property switches will be used to determine particle behaviour.

If we are to preserve algorithmic stability and physical realism while switching between modes, the key requirements are correct interpolation functions, contact detection methods, material models, and heuristics for the transition between the continuum mechanics, rigid body dynamics, and peridynamics modes. MPM provides contact detection automatically but further research is necessary to develop a method to enforce rigid body contact near sharp corners. Standard continuum mechanics material models are too computationally expensive for visual effects simulations. However, since high fidelity to physics is not necessary, models that are simplified and easy to evaluate may suffice. We will explore deformation plasticity models for permanent deformations and develop new anisotropic elasticity and damage accumulation models for anisotropic failure. Homogeneous material properties cannot be used if we want realistic fracture patterns to arise so we will introduce statistical inhomogeneities in the form of aleatoric uncertainties [24] to allow the creation of realistic crack paths.

Spatio-temporal model-order reduction in the context of nonlinear dynamics will be addressed by expressing the semi-discrete equations of motion in a smaller dimensional space, with emphasis on the possibility of using reduced-order Ritz bases [25]. This approach is expected to have the effect of suppressing high frequency vibrational modes but further research is needed into the application of these ideas in multi-material dynamic situations. Also, existing techniques usually involve a global solution and the effective simulation cost is not reduced significantly and solution accuracy may be lost if excessive reduction is performed. Since fracture is a local effect, we will adapt techniques developed for virtual surgery [26] to retain local accuracy while reducing spatio-temporal model order.

Failure heuristics and crack path evolution rules are also critical if near real-time failure simulation is to be achieved and part of our research in Phase 1 will involve the extraction of heuristics from detailed parallel computations. The technique that has been applied in other contexts by the visual effects community is to use precomputed solutions [27] and then reduce the dimensions using a projection to a lower dimensional manifold in phase space using model-order reduction. This programme plans to explore locally linear embeddings [28,29] to perform the needed projections. This technique has been used widely by the machine learning community and involves the mapping of a region of a high dimensional space into a lower dimension and can also be used for model-order reduction. Similar dimension reduction methods have also been for controlling groups of flying robots [30] and some of the local clustering metrics used in these control algorithms will be used to extract geometrical information from simulated fracture data. More advanced statistical techniques for knowledge extraction [31] will be explored in Phase 2 of the programme.

Important implementation issues such as the mapping of discontinuous deformations on to geometries used for computer graphics visual rendering and user control of the spatial distribution of material properties will also be addressed to a small extent in Phase 1 in collaboration with Weta researchers.

Timeframe: Phase 1 of the project will run for two years. A time-task plan for the programme is shown in Figure 1 in the section “Alignment with assessment criteria”.

Research aims:

1. *Computational fracture mechanics:*

Development of algorithms for peridynamics and MPM, development of material models, transitioning between peridynamics and MPM, validation and verification.
Year 1 funding sought: NZD 255,000 (excluding GST).

2. *Model-order reduction:*

Development of homogenized models, implementation of rigid body dynamics, research into reduced-order Ritz bases, transition between deformation and rigid modes, verification and validation.
Year 1 funding sought: NZD 150,000 (excluding GST).

3. *Knowledge extraction:*

Detailed simulations of fracture, research into locally linear embeddings, identification of fracture evolution rules, implementation of heuristics into software.
Year 1 funding sought: NZD 50,000 (excluding GST).

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IRL Intellectual Property Management Plan
Fast physics-based fracture for visual effects

Introduction

Industrial Research Ltd (IRL) has current policies and procedures in place which direct the management of its intellectual property (IP) assets. IRL's IP management process is designed to ensure that all valuable or potentially valuable IP is suitably protected in order to maximise commercial outcomes.

Operational responsibility for IP management at the corporate level is vested in the Deputy CEO. The Deputy CEO is supported by a full time IP Manager who is responsible for the management of all IP protection processes. Significant IP-related decisions and strategies are approved by IRL managers with delegated financial authority according to the level of IP investment proposed. Advice from external expert advisors is sought when the IP investment requested is greater than $25,000. Different IP protection strategies including patenting are considered according to the needs of the programme or project generating the IP.

IP management decisions are consistent with and supportive of IRL's business strategies, commercialisation and technology transfer plans and science strategies. IP and commercialisation decision making is guided principally by commercial imperatives in the context of a portfolio of technology investment opportunities. IRL has a driving vision of creating value for New Zealand with and through its industry partners.

Identification of Valuable IP for Work Programme (PROP-29370-HVMSSI-IRL)

(i) Responsibility of Science Leader **Dr. Biswajit Banerjee** in consultation with Science Team Manager.

(ii) A standing agenda item at regular IRL internal MSI contract review meetings will require the Science Leader to identify any potentially valuable Work Programme IP and raise any opportunities or problems in relation to that IP. Particular consideration is to be given to milestone finish dates and to targeted Specific Outputs where these involve patenting or other IP protection measures.

Decision to Patent Valuable IP – IP Strategy

(i) An initial decision to patent Work Programme IP will be taken jointly by the Science Leader, Science Team Manager and the IP Manager following formal Invention Disclosure. If a multi-party programme management committee exists IRL's decision will be relayed as appropriate. For valuable IP a provisional patent application will be made at the earliest possible date.

(ii) Records will be kept of all IP decision making processes.

(iii) Decisions to advance beyond the provisional patent stage will be subject to review and recommendation by appropriate IRL managers through the IRL PreSeed and IP Investment Committee.

(iv) Prior to the national phase of patenting, an international patent filing strategy will be proposed by the project team consisting of Science Leader, Investment & Commercialisation or Industry Engagement Manager and any other directly involved IRL or external stakeholder including industry partners. This IP strategy will be coordinated and documented by the IP Manager and, following discussions, signed off by IRL management according to normal financial delegations.

(v) If programme IP is to be shared with another contracting partner then decisions in (i), (iii) and (iv) above may be made jointly with that partner subject to the terms of the relevant contract.

Contracting IP co-owner(s): Industrial Research Limited /
Weta Digital Limited

(vi) The IP strategy will, wherever possible, take an IP portfolio approach meaning that individual patenting decisions will be made in the context of the enhanced potential for value creation from a coherent portfolio of related patents.

(vii) IP management decisions will be informed by the results of "patentability" and "freedom to operate" patent searches as appropriate in order to minimise commercial risk and maximise commercial value of the IP.

PROGRAMME IP DETAILS

- Existing IP Landscape

The patented prior art closest to the proposed approach are:
[1] US Patent # US 6,456,289 B1 (Sep 24, 2002) "Animating system and method for animating object fracture" by O'Brien and Hodgins, and
[2] US Patent # US 7,363,199 B2 (Apr 22, 2008) "Method and apparatus for simulating soft object movement" by Reynolds et al.

Published scientific papers in the area include:
[1] Bobaru, F., 2007, Influence of van der Waals forces on increasing the strength and toughness in dynamic fracture of nanofibre networks: a peridynamic approach, Modelling and Similation in Materials Science and Engineering, 15, pp. 397-417.
[2] Xu, J. et al. 2008, Peridynamic analysis of impact damage in composite laminates, J. Aerospace Engineering, 21, pp. 187-194.
[3] Banerjee, B. et al.., 2005, Simulation of impact and fragmentation with the material point method, Proc. 11th international conference on fracture, Turin, Italy.
[4] Muller, M. et al., 2001, Real-time simulation of deformation and fracture of stiff materials, Computer Animation and Simulation 2001, pp. 113-124.
[5] Solenthaler, B. et al., 2007, A unified particle model for fluid--solid interactions, Computer Animation and Virtual Worlds, 18(1), pp. 69-82.
[6] Niroomandi, S. et al., 2012, Real-time simulation of surgery by reduced-order modeling and X-FEM techniques, Int. J. Numer. Meth. Biomed. Engng., doi: 10.1002/cnm.1491.

However, the patented approaches are significantly different from the proposed approach. Also, the proposed approach has not yet been published in the mechanics, animation, or biomedical engineering literature. Based on the patented prior art it is anticipated that patentable New IP will result from this proposal with no freedom to operate problems likely.

- Anticipated new IP

The new work programme will result in the following know how some of which may be published if appropriate, subject to protection of Weta Digitals commercial interests:
- technique to connect peridynamics with the material point method.
- technique for extraction of fracture heuristics from simulation results.
- new material models for fracture of anisotropic and layered materials.

- new mode transition algorithms for improved fracture simulation speed.
- homogenization and other model-order reduction techniques for multi-material fracture simulations in visual effects, virtual surgery, and engineering analysis.

Potentially patentable IP will include the framework of unified simulation of fracture and solid-fluid interaction and the approach for transitioning between various simulation modes.

- Routes to value creation from this new IP

Three industry sectors will be targeted for value creation from this IP: visual effects for arts and media (including motion pictures and computer games), virtual tools for medical training (including virtual surgery), and engineering analysis and design tools. At present, the anticipated mode of commercialization is customization and licensing to relevant industrial partners.

- Visual effects for motion pictures and computer games: The IP created in this program will be integrated with existing tools used by Weta Digita (Weta). Weta will create additional IP from concurrent research on tools for the transfer of geometry to and from simulations (for computer graphics visualization) and user interfaces that can handle multiple interacting materials. These new tools will be used to enhance Weta's reputation for being a company at the forefront in technological advancements that can deliver effects never seen before at a high level of realism. Computer gaming companies such as Stickmen Studios and Sidhe Interactive may also benefit from this IP through licensing agreements with IRL and Weta.
- Virtual tools for medical training: The IP can also be used by medical device companies such as Enztec and Adept Medical for evaluating the ease of installation of implants and for training surgeons. Contacts have been developed with Dr. Phil Blythe and the eLearning initiative at the University of Otago Faculty of Medicine for applications to virtual surgery.
- Virtual fracture for engineering analysis and design: The fast evaluation of the possibility of fracture in engineered components is another path of value creation through this IP. There are no New Zealand companies in this space and there is the potential for a start-up company that can take the technology directly to market as a stand-alone software or as an add-on to existing commercial software products.

Impact statement 1

Short title	Fast fracture simulation techniques
Start Date	01/10/2012
End Date	30/09/2014
Research question	Digital content tools, including imaging
Funding sought p.a. (GST exclusive)	$455,000.00
Funding sought p.a. (GST inclusive)	$523,250.00
IS Leader	Dr Biswajit Banerjee
Primary End User(s)	3D content creation sector Weta Digital Limited

Impact statement

The research will deliver new techniques and software tools for the fast simulation of fractures in nonlinear dynamic contexts. Physical realism will be achieved with a novel hybrid computational approach and new material models. Increased speed of computation will be delivered with a combination of model size reduction methods. Simple rule-based models for fracture growth and spatial distribution will also be developed. These techniques will be verified and validated against high-speed photographic evidence and then communicated to the industrial partner, Weta Digital (Weta). The software tools will be developed on an open-source parallel computing software platform and will not be directly transferred to industry. The industrial partner will investigate issues such as the user interface and the mapping of fractured geometries to computer graphics tools so that techniques developed in this programme can be implemented into production software.

Research aim summary table

Research aim	Title
1.1	Computational fracture mechanics
1.2	Reduction of model size (model-order reduction)
1.3	Knowledge extraction (heuristics)

Impact statement 1 Research aim 1.1

Research aim Sequence	1.1
Research aim Title	Computational fracture mechanics
Research aim Text	A hybrid computational technique will be developed that takes advantage of the in-built fracture capabilities of the peridynamic method and the simultaneous description of solids and fluids that is possible with the material point method (MPM). Material models will be developed that are capable of predicting fracture paths in anisotropic materials such as wood, soft materials such as leather, and composites of soft and stiff materials. Mapping algorithms for transitioning between peridynamics and MPM will be developed. These methods will be implemented and verified in an open-source parallel computing software framework. Results will be validated with high-speed photography of fracture processes. Material models and simulation techniques developed in the process will be communicated to the industrial partner at regular intervals.
Start Date	01/10/2012

End Date	01/08/2014

Impact statement 1 Research aim 1.1 Critical steps

Sequence	1.1.1
Short Title	Implementation of peridynamics
Description	The implementation of peridynamics will involve three steps. A stand-alone code will be developed for testing purposes. This code will then be converted into a form that can be run on parallel machines. The next step will be use the existing framework for MPM as the region of search needed by peridynamics.
Start Date	01/10/2012
End Date	01/05/2013

Sequence	1.1.2
Short Title	Development of material models for fracture
Description	Adequate material models do not exist for the dynamic fracture of anisotropic materials. Models are also needed for soft material fracture allowing for permanent deformations and for the failure of layered materials. The development of these models is critical to the success of the project. The material models also have to be simple enough for a visual effects user to use. These models will be designed with inputs from the industrial partner.
Start Date	01/10/2012
End Date	01/04/2014

Sequence	1.1.3
Short Title	Transition between MPM and peridynamics
Description	The transition between MPM and peridynamics will involve the determination of physical states that can be used as precursors to fracture. Once an object is found to be close to fracture, the peridynamics mode will be turned on and used to drive fracture propagation. For stable computations, accurate mappings between MPM and peridynamics are needed in this step. Fragments of objects have to be identified for accurate contact and graphics rendering. The industry partner will be assisted in the resolution of issues related to mapping the geometry to meshes used for computer graphics.
Start Date	10/01/2013
End Date	01/07/2014

Impact statement 1 Research aim 1.2

Research aim Sequence	1.2
Research aim Title	Reduction of model size (model-order reduction)
Research aim Text	For increased computational speed, it is crucial that the model of physics that is used has an optimal size and level of complexity. Model-order reduction methods will be developed and explored to determine the best model size for physically realistic simulations. The aim is to develop techniques that can be used to make simulations run at significantly higher speeds than are possible with current technology. Spatial homogenization will be used to find the effective properties of parts of deformation objects that are not involved directly in fracture. Rigid body dynamics and associate contact algorithms will be implemented. Techniques will be developed for transition from rigid mode to deformable mode and back. Experimental data from high-speed photography will be used to validate the approach. Homogenization approaches that are developed will be communicated to the industrial partner
Start Date	01/03/2013

End Date	01/09/2014

Impact statement 1 Research aim 1.2 Critical steps

Sequence	1.2.1
Short Title	Development of homogenized models
Description	In this phase of the project, the potential for fracture will be used to determine whether a region is “interesting”. Regions that are not of interest will be assigned homogenized (deformable) or rigid behaviour. Homogenized models will be developed for that purpose. Exploration of other order reduction methods will be part of the homogenization process but are not on the critical path of the project.
Start Date	01/02/2013
End Date	10/01/2014

Sequence	1.2.2
Short Title	Implementation of rigid body dynamics
Description	Implementation of rigid body dynamics will involve two steps. A standalone code will be developed in the first step to test whether requirements will be met. The second step will involve implementation into the parallel computing software used for the other aspects of this project. The implementation will be designed such that the existing infrastructure for MPM can be used for modelling rigid bodies. Special contact detection algorithms may also have to be developed and implemented.
Start Date	01/02/2013
End Date	01/07/2013

Sequence	1.2.3
Short Title	Transitioning from deformable to rigid mode
Description	Algorithms for transitioning from rigid body mode to deformable (MPM) mode will be developed. This involves techniques for partitioning a domain and objects in that domain into “interesting” and background regions, identifying fragments and their relative locations within a region, and their interactions.
Start Date	01/02/2013
End Date	01/06/2014

Impact statement 1 Research aim 1.3

Research aim Sequence	1.3
Research aim Title	Knowledge extraction (heuristics)
Research aim Text	Near real-time simulations are used in the pre-visualization of possible simulation outcomes by visual effects artists. The extraction of knowledge from detailed fracture simulations will be used to extraction rules that will be used to pre-plan fracture paths and the evolution of fractures. These fracture paths will be communicated to the industry partner for implementation into their existing software. Advanced automated
Start Date	01/04/2013
End Date	30/09/2014

Impact statement 1 Research aim 1.3 Critical steps

Sequence	1.3.1
Short Title	Detailed simulations of fracture events

Description	Detailed fracture events will be simulated using the tools developed at various stages of the programme. Events of interest and initial geometries will be identified by the industry partner. Software will be developed to convert complex geometrical information into point sets for MPM and peridynamics calculations. Parallel computing resources from the National e-Science Initiative will be used for these simulations.
Start Date	01/04/2013
End Date	01/07/2014

Sequence	1.3.2
Short Title	Identification of fracture evolution rules
Description	Results from the detailed simulations will be used in the manual identification of fracture geometries and evolution rules. Locally linear embeddings will also be explored but are not in the critical path of the project.
Start Date	01/03/2014
End Date	30/09/2014

Impact statement 1 Subcontracting

Organisation	Year 1	Year 2
University of Auckland	$90,009.45	$90,009.45
University of Nebraska - Lincoln	$31,269.08	$31,269.08
Manukau Institute of Technology	$10,000.00	$10,000.00
New Zealand eScience Infrastructure	$1,600.00	$1,600.00
Total	**$132,878.53**	**$132,878.53**

Summary of impact statement 1 co-funding

Type	Year 1	Year 2
Related In-Kind	$0.00	$0.00
Related Cash	$0.00	$0.00
Direct In-Kind	$30,000.00	$30,000.00
Direct Cash	$0.00	$0.00
Unspecified	$0.00	$0.00
Total	**$30,000.00**	**$30,000.00**

Impact statement 1 direct co-funding in-kind contribution

Direct co-funding in-kind	Status	Year 1	Year 2
Weta Digital Limited	Letter of Intent	$30,000.00	$30,000.00
Total		**$30,000.00**	**$30,000.00**

Summary Tables

Contract Year Requested Funding Summary GST exclusive

IS	Impact statement Short Title	Year 1	Year 2
1	Fast fracture simulation techniques	$455,000.00	$455,000.00
Total		**$455,000.00**	**$455,000.00**

Contract Year Requested Funding Summary GST inclusive

IS	Impact statement Short Title	Year 1	Year 2
1	Fast fracture simulation techniques	$523,250.00	$523,250.00
Total		**$523,250.00**	**$523,250.00**

Subcontracting Summary GST exclusive

Organisation	Year 1	Year 2
University of Auckland	$90,009.45	$90,009.45
University of Nebraska - Lincoln	$31,269.08	$31,269.08
Manukau Institute of Technology	$10,000.00	$10,000.00
New Zealand eScience Infrastructure	$1,600.00	$1,600.00
Total	**$132,878.53**	**$132,878.53**

Co-Funding Summary GST exclusive

Type	Year 1	Year 2
Related In-Kind	$0.00	$0.00
Related Cash	$0.00	$0.00
Direct In-Kind	$30,000.00	$30,000.00
Direct Cash	$0.00	$0.00
Unspecified	$0.00	$0.00
Total	**$30,000.00**	**$30,000.00**

Budget (GST exclusive)

Budget Item	Average Yearly Figure
Personnel	$142,960.79
General Operating Expenses (Include capital purchases up to $5,000)	$17,243.37
Building Depreciation / Rental	$14,220.08
Equipment Depreciation / Rental	$17,530.46
Overheads	$130,166.78
Sub-contracting	$132,878.49
Extraordinary Expenditure *	$0.00
Your total budget for year 1 (GST exclusive)	**$454,999.97**
Average annual budget (GST exclusive)	**$455,000.00**
*	

FTEs

Key Personnel (Year 1 figures)

Contracting organisation

Position	Staff Member	Organisation	IS 1
Contract manager,Key researcher,Leader,Science leader	Dr Biswajit Banerjee	Industrial Research Limited	0.70
Key researcher	Dr Bryan Smith	Industrial Research Limited	0.30
Contact person	Ms Denise Cutler	Industrial Research Limited	
Other	Other Staff	Industrial Research Limited	0.01
Total			**1.01**

Non contracted organisation

Position	Staff Member	Organisation	IS 1
Key researcher	Kumar Mithraratne	University of Auckland	0.15
Student	Fracture Student	University of Auckland	1.00
Student	Model-order Student	University of Auckland	1.00
Student	Manukau Students	Manukau Institute of Technology	0.30
Other	Florin Bobaru	University of Nebraska - Lincoln	0.10
Total			**2.55**

Special Ethical Regulatory Requirements

Not Applicable.

Formal Declaration

Formal declaration

You must submit this application by pressing the button marked ‘Agree’ at the bottom of this screen.

You agree that by submitting this application to MSI, you declare and acknowledge the following:
• I am authorised to submit the application on behalf of the applicant;
• the applicant is a legal entity capable of entering into a contract with MSI;
• the information in the application is correct;
• except for any co-funding arrangements described in the application, the work proposed in the application is not currently funded by another party, and has not received approval for funding from any other party;
• all parties mentioned in the application who are not employed by the applicant have confirmed that the nature and level of their involvement in the work described in the application is correct;
• in completing the application, the applicant has taken into account the requirements of any relevant laws, such as the Hazardous Substances and New Organisms Act 1996, and any consents, approvals, licences, and permits that may be required to carry out the work described in the application; and
• information received and generated by MSI in relation to this application may be released by MSI in accordance with MSI’s external reporting requirements or if required by law, including in accordance with the requirements of the Official Information Act 1982 or the Privacy Act 1993.

Signed by	
Date	

Industry Sector

Sector	IS 1
Engineering Products & Services	100.0%
Total	**100.0%**

New Zealand RS&T Curriculum Vitae

PART 1

1a. Personal details				
Full name	Dr	Biswajit		Banerjee
Present position	Senior Research Scientist			
Organisation/Employer	Industrial Research Limited			
Contact Address	24 Balfour Road, Parnell			
	Auckland		**Post code**	1052
Work telephone	9-920-3611	**Mobile**		
Email	b.banerjee@irl.cri.nz			
Personal website (if applicable)				

1b. Academic qualifications

2002, Ph.D., Mechanical Engineering, University of Utah, Salt Lake City, UT, USA.
1994, MS, Mining Engineering, University of Utah, Salt Lake City, UT, USA
1989, B. Tech., Mining Engineering, Indian School of Mines, Dhanbad, India.

1c. Professional positions held

2008-present, Senior Research Scientist, Industrial Research Limited, NZ.
2007-2008, Research Assistant Professor, Mathematics, University of Utah, USA.
2003-2008, Research Assistant Professor, Mechanical Engineering, Univ. of Utah.
2002-2003, Post-doctoral Research Fellow, Mechanical Engineering, Univ. of Utah.
1996-2002, Research Assistant, University of Utah
1989-1996, Senior Systems Engineer, CMC Limited, India.

1d. Present research/professional speciality

Computational and theoretical solid mechanics, metamaterials, composites, fracture simulation, fluid-structure interaction, statistical variability.

1e. Total years research experience	16 years

1f. Professional distinctions and memberships (including honours, prizes, scholarships, boards or governance roles, etc)

1996-1998, William C. Browning Scholarship, University of Utah, USA.
1993, Mines and Minerals Research Institute Graduate Fellowship, USA.
1989, Longwall Gold Medal, Indian School of Mines, India.

1g. Total number of *peer reviewed* publications and patents	Journal articles	Books, book chapters, books edited	Conference proceedings	Patents
	8	2	2	0

PART 2

2a. Research publications and dissemination

Peer-reviewed journal articles

1. Smith, B. and **Banerjee, B**., 2012, *Reliability of inserts in sandwich composites,* Composite Structures, **94**, 820-829.
2. **Banerjee, B**. and Bhawalkar, A., 2008, *An extended mechanical threshold stress plasticity model. Modeling 6061-T6 aluminum alloy,* Journal of the Mechanics of Materials and Structures, **3**(3), 391-424.
3. Guilkey, J., Harman, T. and **Banerjee, B**., 2007, *An Eulerian-Lagrangian approach for simulating explosions of energetic devices*, Computers and Structures, **85**(11-14), 660-674.
4. **Banerjee, B**., 2007, *The Mechanical Threshold Stress model for various tempers of AISI 4340 steel*, International Journal of Solids and Structures, **44**(3-4), 834-859.
5. **Banerjee, B**. and Adams, D.O., 2004, *On predicting the effective elastic properties of polymer bonded explosives using the recursive cell method*, International Journal of Solids and Structures, **41**(2), 481-509.
6. **Banerjee, B.** Cady, C.M., and Adams, D.O., 2003, *Micromechanics simulations of glass-estane mock polymer bonded explosives*, Modelling and Simulation in Materials Science and Engineering, **11**, 457-475.
7. **Banerjee, B.** and Adams, D.O., 2003, *Micromechanics based prediction of effective elastic properties of polymer bonded explosives*, Physica B, 338, 8-15.

Peer reviewed books, book chapters, books edited

1. **Banerjee, B**., 2011, *An Introduction to Metamaterials and Waves in Composites*, CRC Press, Taylor and Francis.
2. **Banerjee,** B. and Adams, D.O., 2003, Micromechanics-based prediction of thermoelastic properties of high energy materials, in *Constitutive Modeling of Geomaterials,* ed. H.I. Ling et al., CRC Press, New York.

Refereed conference proceedings

1. **Banerjee, B.** and Smith, B. G, 2011, *Reliability analysis for inserts in sandwich composites,* Advanced Materials Research, **275**,234-238.
2. **Banerjee, B.,** 2005, *Simulation of impact and fragmentation with the material point method*, in the Proceedings of the 11th International Conference on Fracture, Turin, March 2005 (electronic), 5 pages.

Patents

Not Applicable

Other forms of dissemination (reports for clients, technical reports, popular press, etc)

Invited Talks

1. **Banerjee, B.**, 2012, *Pretty pictures and predictive simulations with MPM*, Weta Digital Limited, Wellington, 18 Jan 2012.
2. **Banerjee, B.**, 2010, *An introduction to the material point method*, Dept. of Mathematics, University of Auckland, 29 Apr 2010.

Technical reports

1. **Banerjee, B.,** 2011, *Review of CAR report on impact characteristics of a SLED grid*, IRL Report # 36690492.01 (15 pages).
2. **Banerjee, B.,** Chen, J. and Kathirgamanathan, A.**,** 2011, *Comparison of ANSYS elements: SHELL181 and SOLSH190*, IRL Report # 36603300.10 (53 pages).
3. **Banerjee, B.,** 2010, *Extruded corner joint: finite element analysis*, IRL Report # 36603300.05 (44 pages).
4. **Banerjee, B.** and Smith, B, 2009, *Failure criteria for inserts in sandwich composite*s, IRL Report # 36603300.02 (23 pages).
5. **Banerjee, B.**, 2007, *A material point formulation for plasticity*, arXiv:1201.2744v1 (40 pages).
6. **Banerjee, B**., 2005, *Validation of the material point method and plasticity with Taylor impact tests*, arXiv:1201.2476v1 (21 pages).
7. **Banerjee, B**., 2004, *Material point method simulations of fragmenting cylinders*, arXiv:1201.2439v1 (15 pages).

Conference Papers

1. **Banerjee, B**., 2007, *Impact and dynamic failure with the Material Point Method*, 9th US National Conf. on Computational Mechanics, San Francisco, July 2007.
2. **Banerjee, B.** and Bhawalkar, A., 2006, *Numerical simulation of the dynamic compression of a 6061-T6 aluminum metallic foam*, 7th World Conf. on Computational Mechanics, Los Angles, July 2006.
3. **Banerjee, B**., 2006, *A Material Point Method formulation of shells for fluid-structure interaction*, 7th World Conf. on Computational Mechanics, Los Angeles, July 2006.
4. **Banerjee, B.**, 2006, *Validation of strain-rate and temperature dependent plasticity models of copper*, 7th World Conf. on Comp. Mechanics, Los Angeles, July 2006.
5. **Banerjee, B.**, 2005, *Validation of a multi-physics code: Plasticity models and Taylor Impact*, in the Proc. of the Joint Conf. on Mechanics and Materials, Baton Rouge.
6. **Banerjee, B., 2004,** *Material point method simulations of fragmenting cylinders*, in Procs of 17th ASCE Engineering Mechanics Conf., Newark, DE, June 2004.

2b. Previous research work

Research title: Material models for interface failure in the presence of variability
Principal outcome: New experimental technique for determination of cohesive properties of interfaces, new nonlinear material models for polymeric foams.
Principal end-user and contact: FrameCAD and Materials Accelerator, University of Auckland; Prof. Mark Taylor

Research title: Rapid prototyping of metamaterial architectures for wave guiding
Principal outcome: Design and development of 3-D printed architectured materials with novel elastic and wave propagation properties.
Principal end-user and contact: Scientific community; Prof. Sarat Singamneni, AUT

Research title: Advanced failure modelling and simulation of sandwich composites.
Principal outcome: Advanced models of composite failure, evaluation of existing simulation tools used by industry, incorporation of statistical variability into design.
Principal end-user and contact: Center for Advanced Composite Materials, Altitude AI, Gurit-High Modulus, Defence Technology Agency; Dr. Mark Battley.

Research title: Design and strengthening of power utility structures **Principal outcome:** Numerical simulations and experiments on power poles and other support structures **Principal end-user and contact:** Vector Limited and TransNet; Mr. Goran Stojadinovic and Mr. Spencer Winn.
Research title: Finite deformation plasticity and failure with the material point method **Principal outcome:** Parallel numerical simulation software Uintah, advanced material models for rate-dependent plasticity of metals and geomaterials, failure prediction methods that work with the material point method. **Principal end-user and contact:** US Department of Energy, US Office of Naval Research, Scientific community, University of Utah; Prof. Charles Wight.
Research title: Micromechanics and homogenization of solid propellants **Principal outcome:** New micromechanics techniques for finding the effective properties of hig volume fration and high contrast composites. **Principal end-user and contact:** Scientific community, US Department of Energy, University of Utah; Prof. Daniel O. Adams.

2c. Describe the commercial, social or environmental impact of your previous research work

1) Composite Simulation: Analysis of shell elements and corner joints in sandwich composites has improved Altitude AI's understanding of non-obvious errors in routine finite element analysis processes.
2) Power utility structure analysis: The simulations and subsequent experiments have allowed TransNet to markets its product in New Zealand and Australia. Analyses for Vector have increased their confidence in the viability of old power poles and have reduced the number that is discarded each year.
3) Rubber O-rings: The changes to the Siltech O-ring manufacturing process have reduced the rate of rejections from 70% to less than 10%.
4) Material point method: The simulation code Uintah has allowed the University of Utah to obtain more than 7 million USD external funding in addition to the original US-DOE funding (see http://www.uintah.utah.edu/projects.html). The code is also being actively used by Schlumberger Research and Wasatch Molecular.

2d. Demonstration of relationships with end-users

1) Project manager for IRL deliverables for the Advanced Composite Structures and IRL lead for the relationship with Altitude AI.
2) Principal investigator for the Materials Accelerator TRST basis research programme on advanced material models for failure and statistical variability.
3) Project manager and lead researcher for several commercially driven research projects. Customers include DeepWater Ltd., Vector Ltd., the New Zealand Navy, VT Fitzroy, Transnet Ltd., High Modulus Ltd., and RPS Switchgear. Relationships with these customers have led to further projects for IRL.
4) Principal contact for the relationship with Weta Digital who approached us after learning about my expertise on the material point method. Created connections between IRL's business development team and Weta.
5) Co-supervisor and external thesis examiner for several post-graduate and undergraduate students from the University of Auckland and AUT University.

New Zealand RS&T Curriculum Vitae

PART 1

1a. Personal details					
Full name	*Title* Dr.	*First name* Bryan	*Second name(s)* Gerard		*Family name* Smith
Present position	Research Scientist, Medical Device Technologies				
Organisation/Employer	Industrial Research Limited				
Contact Address	24 Balfour Road				
	Parnell				
	Auckland			**Postcode**	1024
Work telephone	09-920-3684		**Mobile**	021-814-534	
Email	bryan.smith@irl.cri.nz				
Personal website					

1b. Academic qualifications

2008, Ph.D., Applied Mathematics, Northwestern University
2003, MSc., Applied Mathematics, Northwestern University
2002, BSE., Biomedical Engineering, Tulane University

1c. Professional positions held

2008-Present, Research Scientist, Industrial Research Limited
2003-2008, Research Assistant, Northwestern University
2001, 2008, Teaching Assistant, Tulane University, Northwestern University

1d. Present research/professional speciality

Computational modeling and simulation of engineering structures.
Mathematical and numerical modeling of biological systems.
Numerical method development.

1e. Total years research experience	10 years

1f. Professional distinctions and memberships (including honours, prizes, scholarships, boards or governance roles, etc)

2004-2007, National Defense Science and Engineering Graduate Fellowship
2003-2008, ARCS Foundation Fellowship
2002-2004, National Science Foundation IGERT Fellowship
2001, Tau Beta Pi – Engineering Honor Society
2001, Alpha Eta Mu Beta – Biomedical Engineering Honor Society

1g. Total number of *peer reviewed* publications and patents	Journal articles	Books, book chapters, books edited	Conference proceedings	Patents
	10			

PART 2

2a. Research publications and dissemination

Peer-reviewed journal articles

- Willmott G.R. and **Smith B.G.**, Modelling of resistive pulse sensing: flexible methods for submicron particles, *The ANZIAM Journal*, In Review (2012).
- Willmott G.R. and **Smith B.G.**, Comment on 'Modeling the conductance and DNA blockade of solid-state nanopores,' *Nanotechnology*, 23 (8), 088001 (2012).
- **Smith B**, and Banerjee B, Reliability of inserts in sandwich composite panels, *Composite Structures,* 94, 820-829 (2012).
- Vaughan Jr., B.L, **Smith B.G**., and Chopp, D.L. The Influence of Fluid Flow on Modeling Quorum Sensing in Bacterial Biofilms, *Bull. Math. Biology*, 72 (5), 1143-1165 (2010).
- Calius, E.P., **Smith, B**., Bremaud, X., and Hall, A. Negative mass sound shielding structures: Early results. *Physica Status Solidi (B),* 246 (9), 2089-2097 (2009).
- Chan, K.L., **Smith, B.G**., Wester, E.C., Sun, H., and Calius, E.P. Flexural wave scattering in a quarter-infinite plate with circular scatterers. *IJSS*, 46 (20), 3669-3676 (2009).
- Wester, E.C., Bremaud, X., and **Smith, B**. Meta-material sound insulation. Building Acoustics, 16 (1), 21-30 (2009).
- **Smith, B.G**., Vaughan Jr., B.L., and Chopp, D.L. The extended finite element method for boundary layer problems in biofilm growth. CAMCoS, 2, 35-56 (2007).
- Vaughan Jr., B.L., **Smith, B.G**., and Chopp, D.L. A comparison of the extended finite element method for elliptic equations with discontinuous coefficients and singular sources. CAMCoS, 1, 207-208 (2006).
- Kargol, A., **Smith, B**., and Millonas, M.M. Applications of Nonequilibrium Response Spectroscopy to the Study of Channel Gating: Experimental Design and Optimization. J. Theor. Biol. 218, 239-258 (2002).

Peer reviewed books, book chapters, books edited

Refereed conference proceedings

Patents

Other forms of dissemination (reports for clients, technical reports, popular press, etc)

- Ten confidential client reports

Conference presentations

- Reliability analysis for inserts in sandwich composites. B. Banerjee and **B. Smith,** Int. Conf. on Structural Integrity and Failure, Auckland NZ (July 2010).
- Nonlinear response of locally reinforced sandwich assembiles subjected to out of plane loading. R.M. Stubbing, M. Battley, B. Banerjee, and **B.Smith**. 9^{th} International Conference on Sandwich Structures, Pasadena, CA (June 2010).
- The Extended Finite Element Method and Foam Evolution, **B.G. Smith** and D.L. Chopp, 10^{th} U.S. National Congress on Computational Mechanics, Columbus OH (July 2009).
- Meta-material sound shields, E. Wester, X. Bremaud, and **B. Smith**, 19^{th} Biennial Conference of the New Zealand Acoustical Society, Auckland (November 2008)
- The extended finite element method for boundary layer problems in biofilm growth, **B. Smith**, B. Vaughan Jr, and D. Chopp, SIAM Annual Meeting, Boston MA (July 2006).

2b. Previous research work

Research Title: Aeroacoustics of Carbon Dioxide Exhaust Holes (2011-present)
Principle outcome: Optimization of CO_2 exhaust holes for a respiratory therapy device
Principle end-user and contact: Fisher & Paykel Healthcare – Lewis Gradon

Research title: Digital Rehabilitation (TRST: 2009-present)
Principal outcome: Creation of industry-research connections for the development of a NZ rehabilitation games industry.
Principal end-user and contact: IRL Medical Devices projects, Game software industry, Medical device industry, and Health providers.

Research title: Human Modelling for Assistive Devices (FRST: 2008-present)
Principal outcome: Development of an inverse kinematic musculo-skeletal model for the analysis of upper limb motion.
Principal end-user and contact: IRL Medical Devices projects, Medical device industry, Health providers, and Sports sector.

Research title: FRST Programme: Advanced Composite Structures (2008-present)
Principal outcome: Analysis of variation in the structural performance of sandwich composites containing stress concentrations.
Principal end-user and contact: Centre for Advanced Composite Materials – Dr. Mark Battley, Sr. Research Associate; High Modulus – Susan Lake, General Manager, Technical Services; Altitude – Gavin Balasingam, Technical Specialist, Interiors; Defence Technology Agency – Brian Shaw, Research Engineer

Research title: FRST Programme: Acoustically Efficient Buildings (2008-present)
Principal outcome: Development of a novel metamaterial for sound insulation.
Principal end-user and contact: Fletcher Building Ltd. - Len McSaveney, Marked Development Manager; BRANZ – Wayne Sharman, Strategic Business Development Manager

Research title: Structural Health Monitoring (IRL Capability Programme: 2008)
Principal outcome: Analytical and numerical techniques for analysing the propagation of flexural waves in bounded thin plates.
Principal end-user and contact: IRL Programmes in medical imaging, Users and developers of NDT Technology, International Scientific Community

Research title: The Extended Finite Element Method for Special Problems with Moving Interfaces (2003-2008)
Principal outcome: Ph.D. Dissertation
Principal end-user and contact: International Scientific Community

2c. Describe the commercial, social or environmental impact of your previous research work

- Provided proof-of-concept models of respiratory and orthopaedic devices for several NZ medical device companies, including Adept Medical, Fisher & Paykel Healthcare, and Enztec
- Conducted a dynamic structural analysis of a novel loudspeaker design for Grail Acousitcs
- Provided preliminary stress analysis of wheel designs for the JetBlack land-speed record attempt

2d. Demonstration of relationships with end-users

- Manage the scientific relationship between IRL and the OSA team at Fisher and Paykel Healthcare
- IRL lead for strengthening collaboration with High Modulus in relation to the Advanced Composite Programme.
- Shared responsibility for developing a close working relationship with Auckland University and Altitude.
- Co-supervisor of two postgraduate students at the Centre for Advanced Composite Materials, University of Auckland

New Zealand RS&T Curriculum Vitae

PART 1

1a. Personal details				
Full name	Dr	Kumar		MITHRARATNE
Present position	Senior Research Fellow			
Organisation/Employer	The University of Auckland			
Contact Address	Auckland Bioengineering Institute			
	70 Symonds Street, Level 6			
	Auckland		**Post code**	1010
Work telephone	09 3737599 X 83011	**Mobile**	0210663845	
Email	p.mithraratne@auckland.ac.nz			
Personal website (if applicable)	http://www.abi.auckland.ac.nz/uoa/kumar-mithraratne			

1b. Academic qualifications

2000	PhD	Mechanical Engineering	National University of Singapore Singapore
1991	MSc with Distinction	Mechanical Engineering	Kings College London University of London, UK
1984	BScEng	Chemical Engineering	University of Moratuwa Sri Lanka

1c. Professional positions held

2012 –	Senior Research Fellow	Auckland Bioengineering Institute University of Auckland
2005 – 2011	Research Fellow	Auckland Bioengineering Institute University of Auckland
2003 – 2004	Research Fellow	School of Architecture University of Auckland
2000 – 2002	Research Fellow	Auckland Bioengineering Institute University of Auckland
1999 – 2000	Research Fellow/ Part-time lecturer	Department of Mechanical Engineering Auckland University of Technology
1996 – 1999	Research Scholar	Department of Mechanical Engineering National University of Singapore
1992 – 1995	Senior Research Officer	Industrial Technology Institute, Sri Lanka
1991 – 1992	Masters Student	Kings College London University of London, United Kingdom
1987 – 1991	Research Officer	Industrial Technology Institute, Sri Lanka
1984 – 1987	Research Officer	Ceramic Research and Development Centre Sri Lanka

1d. Present research/professional speciality

Soft tissue continuum mechanics including contact mechanics, Rigid body mechanics (joint biomechanics), Computational Fluid Dynamics (blood flow), Finite Element Analysis and Finite difference methods.

1e. Total years research experience	16 years

1f. Professional distinctions and memberships (including honours, prizes, scholarships, boards or governance roles, etc)

2003-2004 University of Auckland Post-doctoral fellowship
1996-1999 Research Scholarship, National University of Singapore
1991-1992 British Government Technical Corporation fellowship

Full member of International Society of Biomechanics
Full member of European Society of Biomechanics

1g. Total number of *peer reviewed* publications and patents	Journal articles	Books, book chapters, books edited	Conference proceedings	Patents
	15	02	39	01

PART 2

2a. Research publications and dissemination

Peer-reviewed journal articles

1. Bradley, C., Bowery, A., Britten, R., Budelmann, V., Camara, O., Christie, R., . . ., **Mithraratne, K**., ... Hunter, P. (2011). OpenCMISS: A multi-physics & multi-scale computational infrastructure for the VPH/Physiome project. *Progress in Biophysics and Molecular Biology*, *107*(1), 32-47.

2. Ho, H., **Mithraratne, K.**, Schmid, H., Sands, G., & Hunter, P. (2010, January). Computer simulation of vertebral artery occlusion in endovascular procedures.. *Int J Comput Assist Radiol Surg*, *5*(1), 29-37. doi:10.1007/s11548-009-0379-x

3. Oberhofer, K., **Mithraratne, K.**, Stott, N. S., & Anderson, I. A. (2009, September). Anatomically-based musculoskeletal modeling: prediction and validation of muscle deformation during walking. *Visual computer*, *25*(9), 843-851. doi:10.1007/s00371-009-0314-8

4. Ho, H., **Mithraratne, K.**, & Hunter, P. (2009). A computational model for cerebral circulation and its application for haemodynamic modelling in vascular surgeries. *J Physiol Sci*, *59*, 501.

5. Ho, H., Sands, G., Schmid, H., **Mithraratne, K.**, Mallinson, G., & Hunter, P. (2009). A hybrid 1D and 3D approach to hemodynamics modelling for a patient-specific cerebral vasculature and aneurysm.. *Med Image Comput Comput Assist Interv*, *12*(Pt 2), 323-330.

6. Oberhofer, K., **Mithraratne, K.**, Stott, N. S., & Anderson, I. A. (2009, January 5). Error propagation from kinematic data to modeled muscle-tendon lengths during walking.. *J Biomech*, *42*(1), 77-81. doi:10.1016/j.jbiomech.2008.10.007

7. Oberhofer, K., Stott, N. S., **Mithraratne, K.**, & Anderson, I. A. (2010, January). Subject-specific modelling of lower limb muscles in children with cerebral palsy.. *Clin Biomech (Bristol, Avon)*, *25*(1), 88-94. doi:10.1016/j.clinbiomech.2009.09.007

8. Fernandez, J. W., **Mithraratne, K.**, Thrupp, S. F., Tawhai, M. H., & Hunter, P. J. (2004, March). Anatomically based geometric modelling of the musculo-skeletal system and other organs.. *Biomech Model Mechanobiol*, *2*(3), 139-155. doi:10.1007/s10237-003-0036-1

9. Al-Jumaily, A. M., & **Mithraratne, K.** (2001). Simulation of respiratory system for identifying airway occlusion. *Int J Nonlinear Sci*, *2*(1), 21-28.

Peer reviewed books, book chapters, books edited

1. Fernandez, J.W., Hunter, P.J., Shim, V., & **Mithraratne, K.** (2012), ‘A subject-specific framework to inform musculoskeletal modelling: Outcomes from the IUPS Physiome Project’ In: Begoña, C., & Peña, E. (Eds.), Lecture Notes in Computational Vision and Biomechanics: Patient-specific Computational Modelling, Germany, Springer. Accepted.

2. Cheng, L.K; Hunter, P.J; **Mithraratne, K**; Pullan, A.J; Remme, E.W; Reynolds, H.M; Smith, N.P; Yassi, R.S. 'Clinical applications of physiome project models', In: Mark Atherton, (Ed.) *Repair and Redesign in Physiological Systems,* 2006.

Refereed conference proceedings

1. Greybe, D., Boland, M., Fernandez, J., & **Mithraratne, K.** (2011). A method for defining a finite-axis of rotation in complex joint systems. *Medical Sciences Congress*. Queenstown, New Zealand.
2. **Mithraratne, K.**, Son, J., Hunter, P. J., & Fernandez, J. (2011). A coupled solid-fluid computational model for predicting blood transport in the diabetic foot. In *XXIIIrd Congress of International Society of Biomechanics*. ULB - VUB Campus, Brussels, Belgium.
3. Fernandez, J., Jor, J., Ul Haque, M., Jacobs, M., Hunter, P. J., & **Mithraratne, K.** (2011). Nerve excitation in the diabetic foot: An anatomically based model to explore mechano-stimulation of sensory nerves. In *XXIIIrd Congress of International Society of Biomechanics*. ULB - VUB Campus, Brussels, Belgium.
4. **Mithraratne, K.**, Hung, A., Wu, T., Sagar, M., & Hunter, P. J. (2011). Simulating facial expressions using an efficient heterogeneous continuum model. In *XXIIIrd Congress of International Society of Biomechanics*. ULB - VUB Campus, Brussels, Belgium.
5. **Mithraratne, K.**, Hung, A., Sagar, M., & Hunter, P. J. (2010). An efficient heterogeneous continuum model to simulate active contraction of facial soft tissue structures. In *IFMBE Proceedings* Vol. 31 (pp. 1024-1027). Suntec Convention Centre, Singapore.
6. Wu, T., **Mithraratne, K.**, Sagar, M., & Hunter, P. J. (2010). Characterizing facial tissue sliding using ultrasonography. In *IFMBE Proceedings* (pp. 1566-1569). Suntec Convention Centre, Singapore.
7. **Mithraratne, K.**, Shim, V., Anderson, I., & Hunter, P. J. (2010). A computational framework to estimate in vivo contact pressure in femoral-pelvic articulation during level walking. In *European Orthopaedic Research Society*. Davos, Switzerland.
8. **Mithraratne, K.**, & Hunter, P. J. (2010). Anatomically based, computationally accurate and efficient finite element model of skeletal muscle for large deformation mechanics. In *17th Congress of the European Society of Biomechanics*. University of Edinburgh, United Kingdom.
9. Hung, A., & **Mithraratne, K.** (2010). Investigate the use of membrane-solid coupling for simulating deformation of heterogeneous soft tissue under compression. In *IFMBE Proceedings* (pp. 1028-1031). Suntec Convention Centre, Singapore.
10. Oberhofer, K., Stott, N. S., **Mithraratne, K.**, & Anderson, I. A. (2010). The use of subject-specific lower limb models in research related to cerebral palsy. In *Developmental Medicine and Child Neurology* Vol. 52 (pp. 66). Christchurch, New Zealand. doi:10.1111/j.1469-8749.2009.03595.x
11. **Mithraratne, K.**, Lavrijsen, T., & Hunter, P. J. (2009). A Coupled Soft Tissue Continuum-Transient Blood flow Model to Investigate the Circulation in Deep Veins of the Calf under Compression. In C. T. Lim, & J. C. H. Goh (Eds.), *13TH INTERNATIONAL CONFERENCE ON BIOMEDICAL ENGINEERING, VOLS 1-3* Vol. 23 (pp. 1878-1882). Singapore, SINGAPORE: SPRINGER.

Patents
Anderson, I.A; Gilmour, R.F; Hunter, P.J; Malcolm, D.T.K, **Mithraratne, K**; et al., "Integrated-Model Musculoskeletal Therapies", USA, US2011/0112808 A1, 2011.
Other forms of dissemination (reports for clients, technical reports, popular press, etc)
Mithraratne, K; Transformation of mesh nodal values and derivatives, 2002.   **Mithraratne, K**; Host mesh fitting, 2002.

2b. Previous research work

Research title: Biomechanics for Animation – Funded by FRST
Principal outcome: Anatomically accurate biomechanical of the human face for simulating facial expressions
Principal end-user and contact: Weta Digital Ltd.

Research title: Expressive Head and Hands – Funded by MSI/TechNZ/Weta Digital
Principal outcome: In progress
Principal end-user and contact: Weta Digital Ltd.

2c. Describe the commercial, social or environmental impact of your previous research work

The anatomically based facial model developed was the first of its kind as it was based on Hermite family finite elements. These elements ensure physics involved in nonlinear or large deformation of soft tissue is accurately modelled. Furthermore, the model was driven by activating relevant facial muscles with very accurate fascicular orientations.

2d. Demonstration of relationships with end-users

The outcomes of the MSI/TechNZ/Weta funded project (Expressive Head and Hands) are designed to resolve and improve the current modeling framework in Weta's animation pipeline. This will enable Weta to gain a competitive advantage over its rivals.