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SIMULATING DINOSAUR TRACKWAY FORMATION

Lee Margetts[*]**, Ian M. Smith**[†]**, Joanna M. Leng**[*] **and Phillip L. Manning** [††]

[*] Manchester Computing, University of Manchester, M13 9PL
lee.margetts@manchester.ac.uk, joanna.leng@manchester.ac.uk

[†] School of Mechanical, Aerospace and Civil Engineering,
University of Manchester, M60 1QD
ian.smith@manchester.ac.uk

[††] Manchester Museum,
Oxford Road, Manchester, M13 9PL
phil.manning@manchester.ac.uk

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Summary. *Palaeontologists recognise that they have a tough challenge when faced with determining how dinosaurs went about their day to day activities, for example how fast they could run and whether bipedal examples walked with the upright gait typical of museum displays. Apart from the occasional pile of petrified bones, the only other clues available are track-ways or fossilised footprints. Even these are contentious, with disagreement as to whether track morphology can be used to identify different species. As well as the morphology of the footprint itself, in the three-dimensional zone beneath, sedimentary deformations provide a snapshot of how the ancient sediment responded to loading. The nature of these plastic deformations depends on many factors - sediment composition, humidity and how the loading was applied. In soil mechanics, there are many plasticity models that could be applied to help back-figure the prevailing conditions and thus how the dinosaur walked. In essence, a footprint simulation would be no different from one carried out for a foundation design. However, there are many features that would make it perhaps more computationally demanding: Firstly the loading will have been applied obliquely and secondly the fine scale structure of the soil needs to be adequately represented. Both these factors mean that the problem is irreducibly three-dimensional. Capturing the level of detail required to compare field, laboratory and computational studies, means that plasticity problems with tens of millions of degrees of freedom must be solved. This paper looks at how parallel processing techniques developed for large-scale geomechanics problems may be used to provide further insight into dinosaur locomotion.*

1 INTRODUCTION

Fossil dinosaur tracks have the potential to reveal information on the size[1], gait[2] and speed[3] of dinosaurs, their locomotor evolution[4], as well as providing clues to their behaviour[5]. Furthermore, the tracks, together with the surrounding sedimentary rocks, are the record of the global Mesozoic terrestrial environments and ecosystems[6]. When interpreted correctly, all vertebrate tracks (not just dinosaurs) can potentially unlock past environments, behaviour and ecology, and therefore their study has wide ranging application to themes such as biodiversity and environmental change.

The underlying assumption of many interpretations (through 100 years of literature) is that what is preserved is a surface track. Therefore, data (e.g. track length & width, digit length, number of digits, interdigital angles) on which these interpretations are based are recorded as 2D features. However, the study of vertebrate tracks and traces, vertebrate palaeoichnology, has concentrated on describing the trace with little or no interpretation of track formation and preservation. The way in which sediments behave before, during and after a track is formed, and the subsequent processes that may further modify a track have, been essentially neglected.

Allen[7] and Manning[8] suggest that fossil tracks are not simply 2D surface traces of the maker's foot, but most are complex three-dimensional volumes associated with deformation at the surface and in the shallow (few 10s of cm) subsurface associated with each step. Pilot experiments undertaken by Manning[8] have recovered subsurface track layers yielding, for the first time, detailed information on subsurface track morphology that could be related to ‘true’ surface trace features. It is clear from this study that many tracks have been misinterpreted as surface traces when, in fact they are transmitted features that are markedly different in size and morphology to the surface traces.

The differences described have a major impact on interpretations based on the analysis of tracks. For example, when track length is used in calculations to determine the speed of a walking dinosaur[3], estimated speed can be an order of magnitude higher if measurement is taken within the subsurface deformed zone relative to the true surface trace. Caution should also be applied when ‘estimating’ population dynamics from fossil track assemblages[5]. Taxonomic characters, such as track morphology and geometry, that are currently used to define ichnotaxa have been clearly shown to vary with depth within a 3D track volume, substrate type and prevailing environment[8], making many ichnotaxa questionable and the animal interpretations derived from them invalid. These simple observations have profound implications for the interpretation of dinosaur tracks, and the broader interpretations that are derived from the analysis of all fossil tracks.

2 COMPUTATIONAL STRATEGY

These issues have led Manning, a Palaeontologist by training, to look towards computational plasticity as it promises to enable a detailed investigation of the 3D deformation associated with track formation.

2.1 Plasticity in track formation

Sediment/limb interaction during footfall creates an elastic/plastic deformation cycle resulting in both elastic compression and rebound and permanent plastic shear within the soil with the load/unload cycle of the foot. Realistic simulation of the process requires the faithful replication of the distribution of load exerted by a foot during both walking and running modes.

Loading information has been captured by Manning using a live emu (a relative of theropod dinosaurs) walking across a pressure sensitive platen. Ultimately such information can be used to in a numerical analysis. However, for our preliminary work, we assume a uniform distribution.

2.2 Parallel Solver

As stated in the abstract, complexities in foot geometry, soil properties and the loading cycle mean that a 3D analysis is necessary. With large non-linear 3D problems, parallel processing is a distinct advantage and the authors use a parallelized element-by-element solution strategy that is described elsewhere[9,10].

When using a direct solver, loading is often applied over many linear increments. Such linearization enables reuse of the factorisation of the global stiffness matrix. Another approach is to periodically reform the global matrix, reducing the number of required load-steps. Unfortunately, the global matrix must be refactorised – an operation with prohibitive cost for large 3D problems. Using an element-by-element iterative solver, a global matrix is never created and factorisation is never performed. The stiffness matrices can be reformed cheaply and in an embarrassingly parallel process – i.e. with no communication. Reforming the stiffness matrices means that fewer load increments need to be applied, thus further contributing to the reduction in solution times experienced through parallel processing.

2.3 Interactive Simulation Environment

3D analyses with many incremental load steps and a range of parameters to be explored has the potential to give rise to a data mining problem in the post-processing stage. Therefore the authors have chosen to take advantage of work carried out for an Automotive/Aerospace project[11] in which parallel processing is used to enable simulations to be carried out interactively as well as in batch mode. Here, interactive implies a cycle time of seconds for modifying the model, solution time, results recovery and visualisation. Interactive low-resolution elastic and elasto-plastic analyses can be used to narrow the parameter space to be investigated before undertaking more time-consuming high-fidelity runs in batch mode.

The work uses RapidFire, an interactive simulation environment developed at the EPSRC funded Advanced Virtual Prototyping Research Centre (www.avprc.ac.uk). RapidFire uses the ParaFEM (www.parafem.org.uk) library to deliver impressive, scalable performance using up to 500 processors. The visualisation, compute and interactive functionalities used in RapidFire are distributed across several machines using the RealityGrid steering library[12]. This enables appropriate resources, such as independent high performance visualisation hardware, to be used to accelerate visualization performance as and when required.

Both the RealityGrid and AVPRC projects adopted a flexible component-based approach to software design. The key idea is that isolated components can be coupled together to form bespoke applications. In the RealityGrid project, the steering library was written that could enable a scientist to interact with, deploy, checkpoint and migrate essentially legacy software from one platform to another on the Grid. Only slight modifications to the legacy software are required – with a real emphasis on the word “slight”. AVPRC’s finite element software was designed from the other perspective. A novel finite element analysis library was specifically designed to facilitate interactivity.

The software developed in both the RealityGrid and AVPRC projects is truly scalable. If the problems are small, interactive simulations can be carried out serially, on a desktop machine. Using the same software, access to multi-processor systems is facilitated seamlessly, thus allowing the user to maintain interactivity for larger problems without a change in working behaviour. It is this type of "behind the scenes" scalable, on-demand, HPC application that is desired by industry.

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