Automatically designing the behaviours of falling paper

The emergence of non-trivial behaviours via interaction with the physical world

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ABSTRACT

Biological systems exhibit extraordinary levels of diversity. Embodied behaviours are the emergent property of many loosely-coupled parallel processes, from the microscopic level, e.g. materials, to more abstracted levels, e.g. organs and limbs. We summarise our investigations into using a synthetic methodology, i.e. an understanding-by-building approach, for designing the complex interactions of falling paper shapes. By studying how simple systems such as a falling paper shape behave, we can analyse the specific characteristics of the interaction between morphology and the environment, and how this leads to programmable non-trivial behaviours. We present current results and discuss the implications on the future of design in robotics.

CCS CONCEPTS

• **Computer systems organization** → *Evolutionary robotics*; *Robotics*.

KEYWORDS

Automatic design, Falling paper

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1 INTRODUCTION

From simple cellular organisms to the most complex lifeforms, biological systems exhibit extraordinary levels of diversity. The apparently coherent behavioural repertoires observed in nature seem to stem from the complex *embodied* interaction between the physical and informational worlds [2, 6]. Understanding how (or whether) embodied artificial lifeforms, i.e. robots, can exhibit similar levels of autonomy, cognition and diversity as seen in nature is a key research question. Harnessing the power of evolutionary and developmental algorithms could be the answer to creating robots with these features. Paradoxically however, it seems that roboticists are often torn between dreams of this design autonomy and an instinct to control every aspect of the design process [1].

A key characteristic of biological systems is that interaction with the physical world is driven by many loosely-coupled parallel processes, from the microscopic level, e.g. on the scale of materials, to more abstracted levels, e.g. organs, limbs. Complex behaviours, therefore, are emergent from specific configurations of these interaction processes. In contrast, conventional robotics actively minimize these interactions by using rigid materials, simple joints and actuation, and specifically placed sensors and grippers.

The goal of our research is to use a bottom-up, synthetic methodology to investigate how to design behaviours that emerge from complex physical interactions. In this context, we are interested in systems with a *simple* embodiment but *complex* interaction with the environment. By manipulating non-organic raw materials such as paper, we can analyse the specific characteristics of the interaction between morphology and the environment, and how this leads to non-trivial behaviours. Ultimately, we hope to use this bottom-up approach to understand the principles that drive the emergence of embodied behaviours from physical interactions, and how to harness this in the framework of evolutionary robotics.

2 FALLING PAPER

We focus on the 'Falling-Paper Problem' [5], where paper shapes are released into free-fall and their behaviours observed. Though conceptually a very simple system, falling paper manifests a range of interesting properties.

(1) Interaction-driven complexity. Paper as a material is easily defined by its mechanical properties such as density, elasticity and shape. However, when released into even a simple environment like quiescent air, highly complex fluid-mechanics interactions are induced between the paper and air.

(2) Behavioural diversity. Depending on morphological and environmental factors, the style in which paper falls varies considerably. The stochastic nature of this behavioural emergence means we cannot *guarantee* certain behaviours. Instead, we see certain attractor states to which shapes are highly likely to converge.

(3) Environmental programmability. We can introduce almost infinite richness into the environment by simply adding various air-flows. Hence, we can explore the relationship between, for example, environmental attractor states and behavioural emergence.

(4) Accessibility. Paper shapes can be fabricated, dropped and observed with minimal equipment. Synthetic methodologies are not only feasible, but preferable due to the difficulty in modelling. This makes it an ideal system for studying *real-world* robot development and evolution.

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3 DATA-DRIVEN MODELLING

By utilising a synthetic methodology we can 'outsource' explicit simulation to the target system and use ground-truth data to construct reduced-order models. We have devised and investigated a specific falling-paper system in this context [3]. The V-shaped falling-paper system is a simple paper 'V' shape defined by two morphological parameters: a wing angle θ and wing length l. It exhibits four distinct falling behaviours—plummeting, undulating, helicopter rotation and asymmetric rotation—whose appearance are strongly dependent on morphology (Fig. 1a).

We developed a data-driven modelling technique—physics-driven behavioural clustering—to transform observed falling behaviours into a behavioural parameter space. The approach searches through hundreds of thousands of candidate functions and finds a parameter space that contains clearly distinct regions corresponding to different falling behaviours (Fig.1b).

4 LARGE-SCALE EXPERIMENTATION

The accessibility of falling paper allows us to implement large-scale physical experimentation [4]. Using robotic automation coupled with machine learning, we have created a system that can automatically fabricate and drop hundreds of paper shapes, track their kinematic trajectories in 3D and automatically classify their falling behaviours (Fig.1c-e). This enables us to investigate various properties of falling-paper systems, including the sensitivity of behaviours to changes in the morphology and initial conditions.

Behaviours can broadly be characterised into three categories: steady, tumbling and chaotic. Chaotic behaviours tend to be highly unstructured and seem to correspond to unstable areas in the behavioural parameter space. Tumbling behaviours are the most stable and shapes rarely transition out of this area of the behavioural parameter space. It is relatively easy to design shapes to reliably exhibit these stable behaviour types. We can analyse the programmability of behaviours into the paper morphology with far greater fidelity using data acquired via large-scale physical experimentation.

5 FUTURE DIRECTIONS

Falling-paper research shows how complex and useful behaviours emerge from the interaction between morphology and the environment, and that these interactions can be designed into the system.

A bottom-up approach. Behavioural attractors can be encoded into paper shapes via their morphology, but only realised when released into the environment. Hence, designing for certain behaviours necessitates a strong bottom-up approach, offloading control of the paper to this interaction.

Large-scale physical experimentation. Improvements in rapid fabrication, coupled with broader material usage for robotics (e.g. paper) are enabling orders of magnitude more real-world design experiments to be conducted.

Reality-assisted design. A model can be iteratively constructed and updated using ground-truth data from large-scale physical experimentation. We can treat the model and real-world systems as a unified representation, leading to 'reality-assisted' design. The extent to which design optimisation happens in the real-world

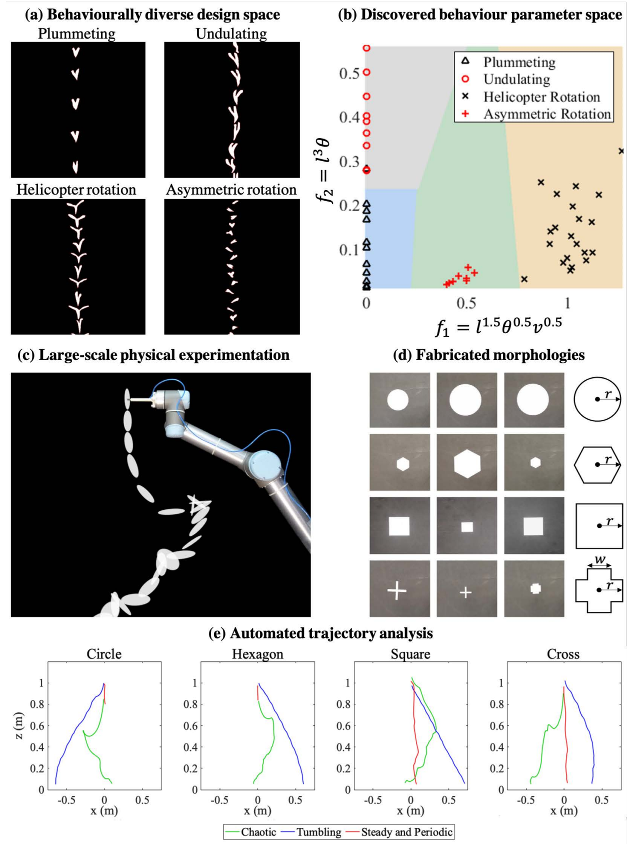

Figure 1: Synthetic methodologies for falling paper, reproduced from our published works [3, 4]. (a) A 'V' paper shape has distinct falling behaviours which depend highly on two morphological parameters (b) A data-driven behavioural parameter space is discovered to best represent these behavioural groups (c) Large-scale physical experimentation using robotic automation facilitates mass data gathering (d) Examples of automatically fabricated shapes (e) Falling shapes are automatically tracked in 3D and classified using machine learning.

can be modulated with respect to the uncertainty of the model representation at that time.

REFERENCES

[1] René Doursat and Carlos Sánchez. 2014. Growing fine-grained multicellular robots. *Soft Robotics* 1, 2 (2014), 110–121.
[2] David Howard, Agoston E Eiben, Danielle Frances Kennedy, Jean-Baptiste Mouret, Philip Valencia, and Dave Winkler. 2019. Evolving embodied intelligence from materials to machines. *Nature Machine Intelligence* 1, 1 (2019), 12–19.
[3] Toby Howison, Josie Hughes, Fabio Giardina, and Fumiya Iida. 2019. Physics driven behavioural clustering of free-falling paper shapes. *PloS one* 14, 6 (2019).
[4] Toby Howison, Josie Hughes, and Fumiya Iida. 2020. Large-scale automated investigation of free-falling paper shapes via iterative physical experimentation. *Nature Machine Intelligence* (2020), 1–8.
[5] Umberto Pesavento and Z Jane Wang. 2004. Falling paper: Navier-Stokes solutions, model of fluid forces, and center of mass elevation. *Physical review letters* 93, 14 (2004), 144501.
[6] Rolf Pfeifer, Max Lungarella, and Fumiya Iida. 2007. Self-organization, embodiment, and biologically inspired robotics. *science* 318, 5853 (2007), 1088–1093.