Reduced-order Modelling for Piano Keystroke with a Soft Particle Jamming Finger

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Abstract

Soft-bodied robotic hand provides a new paradigm for developing intelligent robotic systems with omni-directional flexibility. In this project we proposed a lightweight analytical model to predict the passive behaviours of a piano playing finger with variable material properties. In our system, a particle jamming soft robotic finger was fabricated to perform keystrokes on a piano. The non-linearity of soft-finger contact was modelled as a 2-DoF mass-spring-damper system, allowing the keystroke action to be analytically characterized and predicted. A state-space model was presented to show the keystroke as a single-input multiple-output (SIMO) system and to study the dynamic system's behaviour under varied stiffness conditions. The experimental results demonstrate that the analytical model can represent the dynamics in finger-piano keystroke process throughout a wide range of soft finger stiffness. The method can be a valuable substitute for analysing the high-order compliance of soft-bodied manipulation. It also has potential to serve as a feedforward model for soft robot decision making on keystroke actions.

Objectives

In this work, we proposed an analytical model to depict the piano keystroke action with a variable-stiffness finger. The soft finger-key contact is mechanically depicted as a two degree-of-freedom (DoF) mass-spring-damper system. A state-space model is then developed to represent the dynamic system and predict the behaviour of the compliant interactions under various stiffness settings. To evaluate the proposed model, we fed the model with system-identified stiffness and damping coefficients. The experimental results indicate that the model can represent the piano keystroke with a stiffness-adjustable soft finger in terms of displacements and can be used to predict the generated MIDI signal.

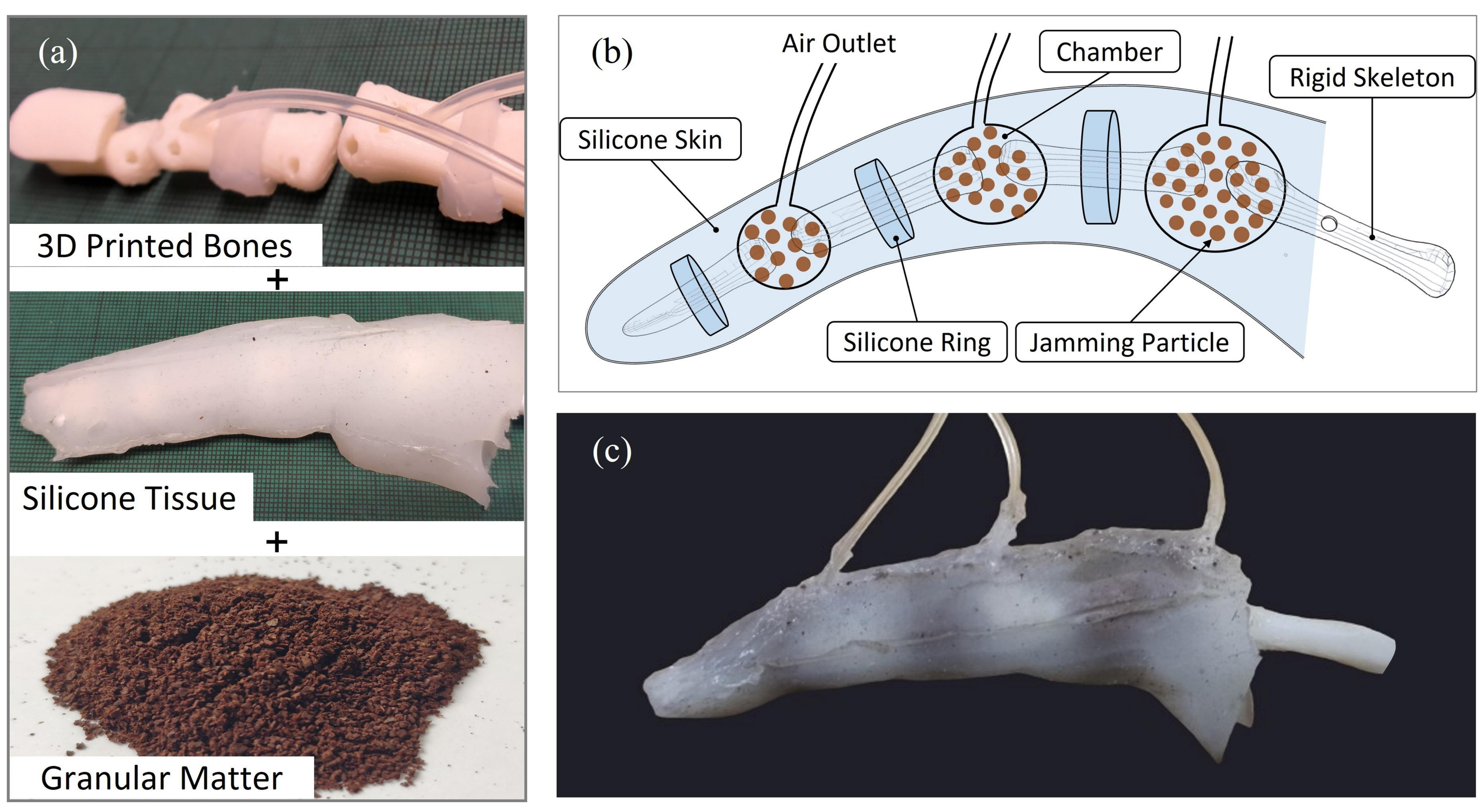
This project makes a number of contributions:

- Development of an analytical, lightweight and reduced-order model for soft-bodied piano keystroke.
- Mathematically formulation of a state-space model to analyse the high-order non-linearity of soft deformation under variable stiffness conditions.
- Fabrication of an anthropomorphic finger with a variable-stiffness finger based on particle jamming.

Materials and Fabrication

The finger is designed as a hybrid of soft and rigid system, with a 3D printed skeleton (Rigur RGD450) wrapped in a casted silicone skin (Ecoflex™ 00-30 rubber). The finger joints are filled by ground coffee acting as the media of particle jamming. Silicone rings are placed around the skeleton between joints to prevent granular particle transition between adjacent chambers, such that an independent vacuum chamber is formed at each joint. PVC tubes are installed in holes left on skeleton to connect the particle jammed joints to a pneumatic regulator. A tiny piece of cloth is stuck to the end of each air tube to prevent the coffee powder from being inhaled in and blocking the tube. After assembly, the whole finger is dipped into liquid silicone for air tightness enhancement.

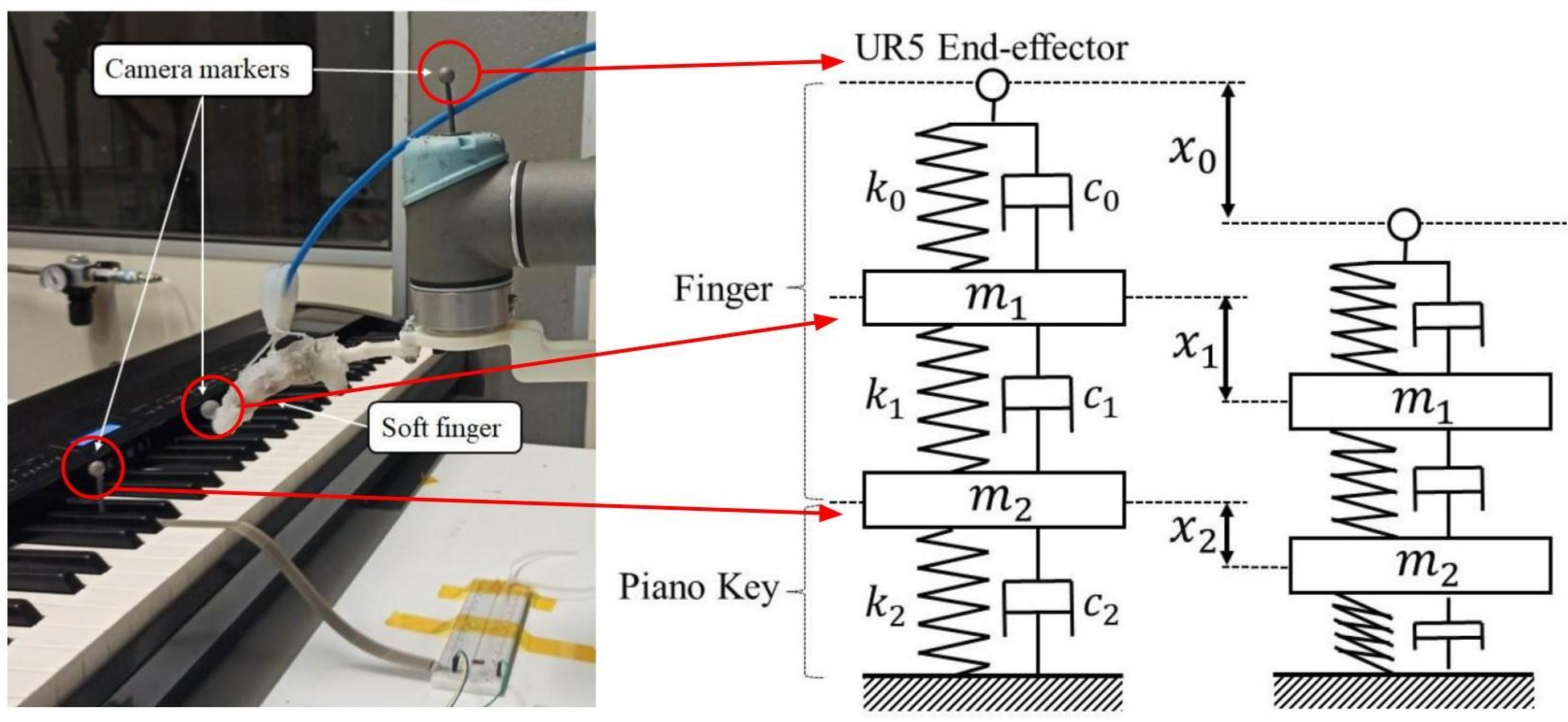
The root of the particle jamming soft finger was mounted on a 6-DoF UR5 robot arm. The variable stiffness fingers were powered by a vacuum pump and controlled by regulators. The vacuum pressure varied from 0 to up to -80 KPa relative to atmospheric pressure. A Kawai ES8 digital piano was used for the experiments, which generated the MIDI messages for keystrokes.



The fabrication of the variable stiffness finger. (a) Materials include the 3D printed skeleton with silicone ring and tubing, silicone skin, and granular ground coffee; (b) Schematic of the particle jamming; (c) Fabricated soft finger.

We focused on the MIDI on velocity generated by the piano in each keystroke, which reflects pressing velocity of the piano key. We applied a 3D infrared motion capture systems (OptiTrack) to record the detailed movement of soft finger in a keystroke action. By adding reflective markers to the UR5 end-effector, the soft finger's tip and the piano key surface, their displacements are captured in 3D space at a frequency of 120 Hz with a precision of 0.001m.

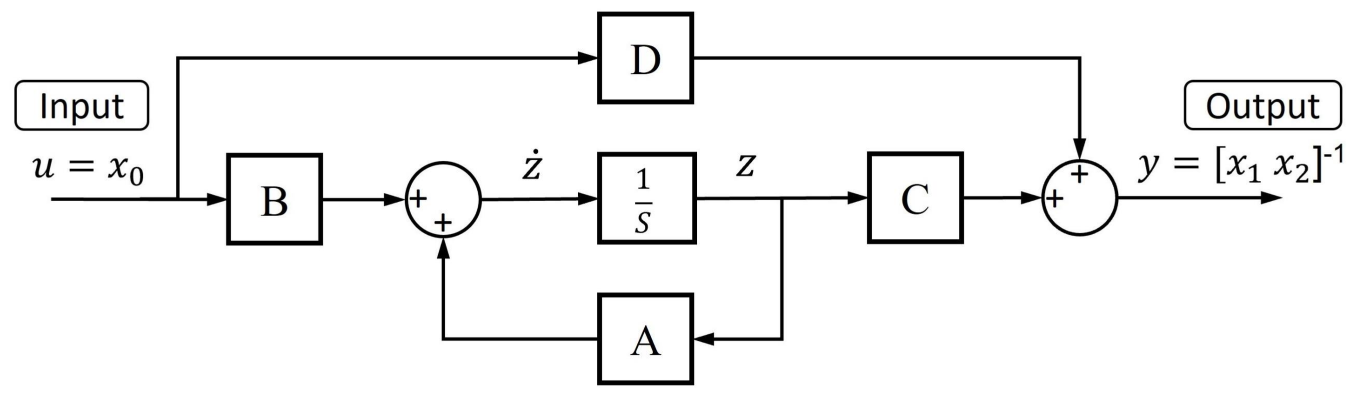
Theoretical Model



To represent the finger-key system during a keystroke, we employed a linear 2 DoF mass-spring-damper model. We used system identification approach to get the stiffness of the particle jamming finger under different vacuum conditions, and the stiffness of the piano key. By examining the captured keystroke waveform by camera tracking system, we estimated the damping coefficient using the logarithmic decrement method and natural frequency. The markers and their corresponding masses in the model are shown in above figure. The model's dynamic equations are:

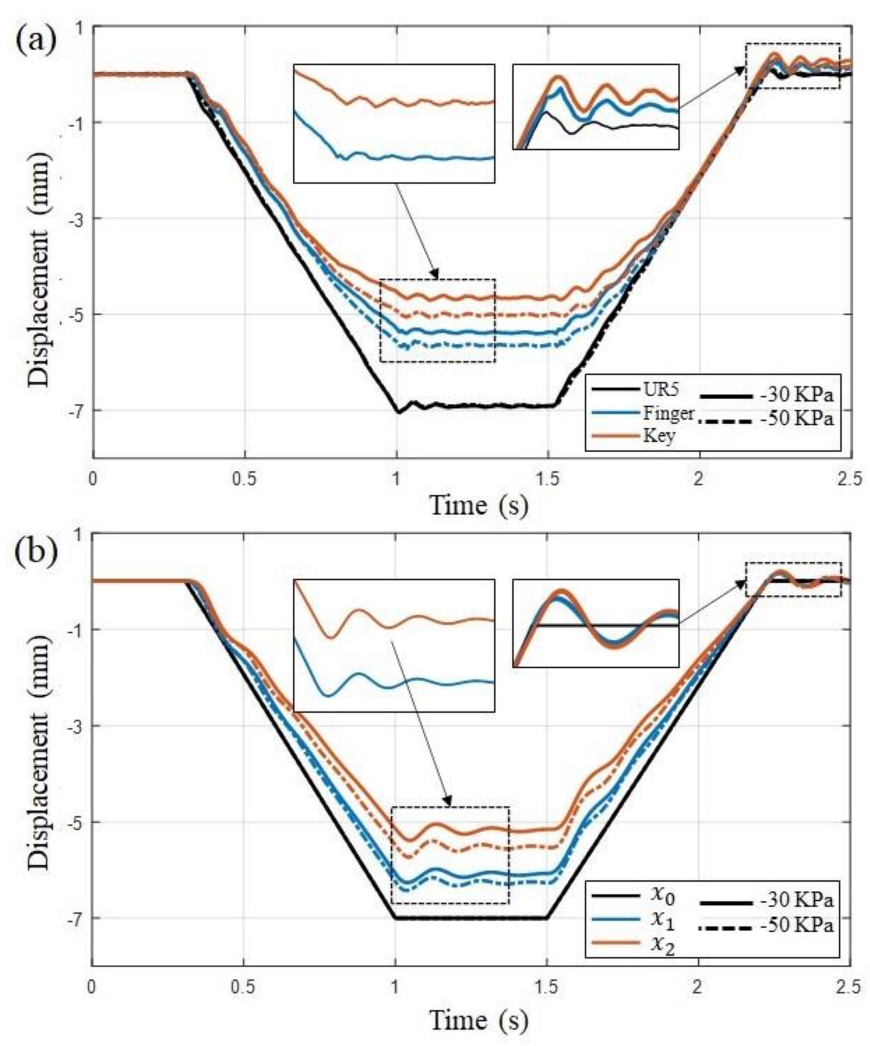
$$\begin{cases} m_1\ddot{x_1} = k_0(x_0 - x_1) - k_1(x_1 - x_2) + c_0(\dot{x_0} - \dot{x_1}) - c_1(\dot{x_1} - \dot{x_2}) \\ m_2\ddot{x_2} = k_1(x_1 - x_2) - k_2 x_2 + c_1(\dot{x_1} - \dot{x_2}) - c_2\dot{x_2} \end{cases}$$

To analyse the behaviour of the mass-spring-damper system, we proposed a single-input multiple-outputs (SIMO) state-space model as below, where input u is the UR5 displacement, and output y is a vector containing the displacement of soft fingertip and the piano key.



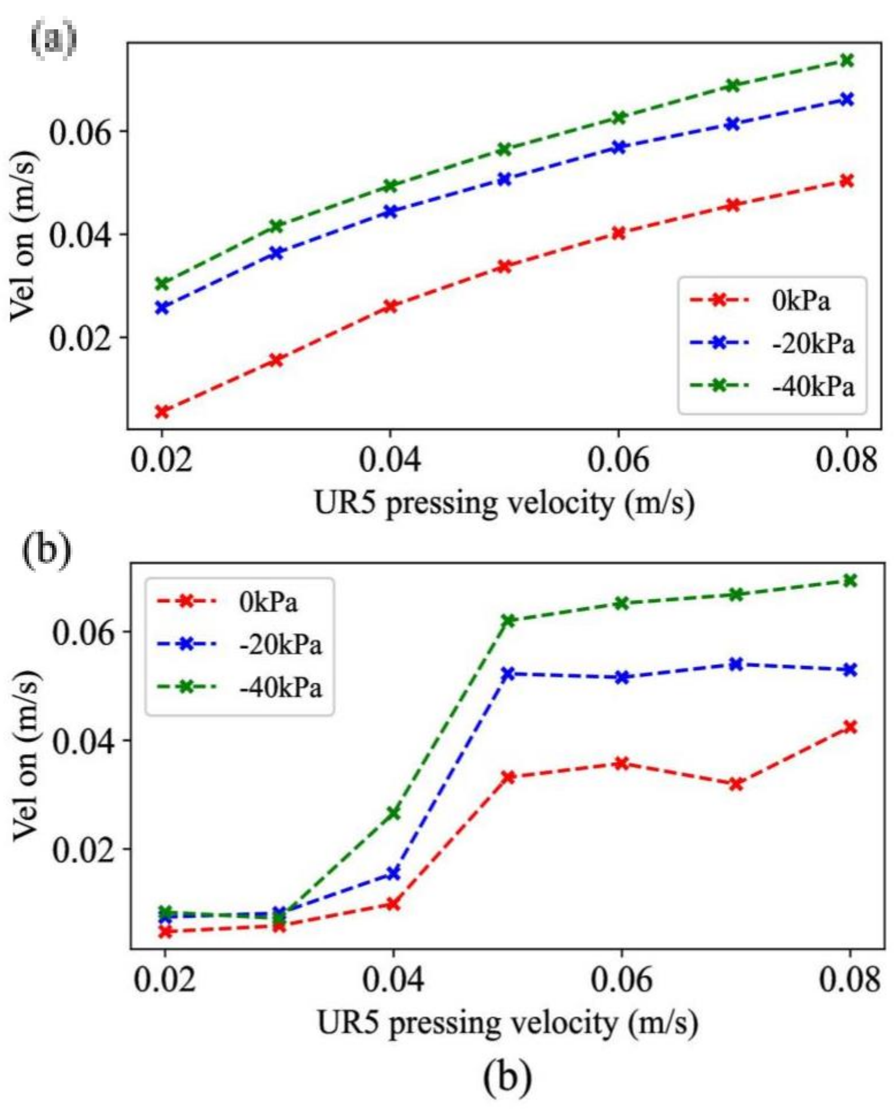
State-space model of the mass-spring-damper system.

Results and Conclusion



Comparison of marker displacements during a keystroke between the (a) analytical model and (b) ground truth.

The model can simulate all the 5 stages of the keystroke action. The damped behaviour of the model matches with the ground truth.



Comparison of MIDI velocity signals (top-left) and holding time (top-right) for the Comparison of the normalized MIDI velocity from (a) analytical model and (b) ground truth. Vel on denoted the normalized MIDI pressing velocity.

An analytical model that can depict real-world keystroke action in piano playing scenario has been proposed. The soft-bodied finger-piano interaction is represented as a second-order mass-spring-damper system. A state-space model, which is lightweight and mathematically analytical, is used to represent the dynamic behaviours of piano keystrokes under varying stiffness conditions. The experimental results reveal that the presented model accurately depicts the passive movements of the finger-piano interaction, while there are real-sim gap in the model MIDI prediction.

This work demonstrated that the behaviours of high-order, non-linear and soft-bodied interactions can be modelled as a linear time-invariant system. The method is promising to serve as a general approach to representing a category of soft-bodied manipulation tasks that can occur repeatedly, such as mouse clicking, keyboard typing, and doorbell pressing. It also has potential to be developed into a feedforward model for soft robot decision making on keystroke actions.