

Digital Twins of Common Swing Door of House

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Abstract— This research paper presents a comprehensive exploration into the creation and utilization of a real-life digital twin for a conventional door, leveraging technology to enhance accessibility and security in smart environments. The digital twin is designed to capture and replicate the door's physical attributes, behaviour, and interactions within a smart environment. To validate the effectiveness of our proposed digital twin model, we conducted extensive experiments in both controlled and real-world environments. The results demonstrate the system's ability to accurately replicate the door's behaviour, predict potential issues, and optimize its performance in response to dynamic conditions. This research contributes to the growing body of knowledge on digital twin applications by showcasing a practical implementation in the context of a commonplace object. The findings provide valuable insights for designing intelligent and adaptive systems, paving the way for future advancements in the field of smart environments and Internet of Things (IoT) applications.

Keywords—

I. INTRODUCTION

Digital twin technology has become increasingly prevalent across numerous sectors, revolutionizing the way we understand and interact with complex systems. From revolutionizing manufacturing processes to optimizing healthcare delivery, its applications are diverse and far-reaching. However, amidst the grandeur of its applications, there lies an often-overlooked realm—the mundane yet essential element of our daily lives: doors.

Doors, those seemingly simple portals, play a pivotal role in our lives, offering access, privacy, and security within our

living and working spaces. As our surroundings evolve into interconnected, intelligent environments, the need for innovative solutions to enhance the functionality and efficiency of everyday objects like doors has become apparent. Herein lies the potential of integrating digital twin technology with conventional doors, presenting an opportunity to address multifaceted challenges in modern smart environments.

The crux of our research endeavours to delve into the dynamic modelling and simulation of a real-life digital twin for doors. Serving as crucial interfaces between the physical and digital realms, doors demand a comprehensive solution capable of adapting to diverse user behaviours, responding to fluctuating environmental conditions, and proactively mitigating security risks.

While digital twin applications abound in various domains, the practical implementation of this technology for commonplace objects like doors has received scant attention. Prior research predominantly focuses on high-complexity systems, overlooking the nuanced challenges associated with everyday objects. Thus, our research endeavours to fill this void by providing a focused exploration of developing and applying a dynamic digital twin model tailored specifically for doors.

A review of existing literature underscores the prevalent oversight regarding the potential of digital twins to enhance the functionality of commonplace objects. This paper seeks to contribute to the field by offering a fresh perspective on the utilization of digital twin technology for doors,

highlighting its adaptability, responsiveness, and predictive capabilities. Our aim is to showcase how leveraging digital twin technology can revolutionize the humble door, elevating it from a mere physical barrier to an intelligent, intuitive element of modern smart environments.

II. MATHEMATICAL MODEL OF SWING DOOR

To generate a mathematical model of a swing door, we'll consider the dynamics involved in its motion. Let's denote the angle through which the door swings as $\theta(t)$, where t represents time. We'll also consider the door's mass, moment of inertia, frictional forces, and external forces applied to it. Here's a simplified model:

1. Newton's Second Law for Rotation:

The rotational motion of the door can be described using Newton's second law for rotation

$$I \cdot \frac{d^2\theta}{dt^2} = \tau_e - \tau_f$$

Where:

I is the moment of inertia of the door.

τ_e is the external torque applied to the door.

τ_f is the torque due to friction.

2. Frictional Torque:

Frictional torque depends on the coefficient of friction (μ) between the door and its hinges, as well as the normal force (N) acting on the door. We can express it as:

$$\tau_f = \mu N r \cdot \text{sgn}(\omega)$$

r is the radius of the hinges.

ω is the angular velocity of the door.

$\text{sgn}()$ is the sign function, returning -1 if ω is negative, 0 if ω is zero, and 1 if ω is positive.

3. External Torque

The external torque can come from various sources such as someone pushing or pulling the door. It can be represented as:

$$\tau_e(t) = \tau_0 \sin(\omega_e t)$$

τ_0 maximum torque

ω_e is the angular frequency of the external torque.

III. INITIAL AND BOUNDARY CONDITIONS

Scenario 1: Free Swing Door

Initial Conditions:

Initial angle:

$$\theta(0) = 0 \text{ (door starts from the closed position).}$$

Initial angular velocity:

$$\frac{d\theta}{dt} = 0 \text{ (door starts from rest).}$$

Boundary Conditions:

- The door is free to swing without any external constraints.
- Frictional torque is present due to the interaction between the hinges and the door, but there are no other external forces.

Scenario 2: Pushed Swing Door

Initial Conditions:

Initial angle:

$$\theta(0) = 0 \text{ (door starts from the closed position).}$$

Initial angular velocity:

$$\frac{d\theta}{dt} = 0 \text{ (door starts from rest).}$$

Boundary Conditions:

- An external torque is applied to the door, simulating someone pushing it.
- Frictional torque opposes the motion of the door.
- The door swings until it reaches a predefined maximum angle, representing its fully open position.

Scenario 3: Damped Swing Door

Initial Conditions:

Initial angle:

$$\theta(0) = \frac{\pi}{4} \text{ (door starts from the closed position).}$$

Initial angular velocity:

$$\frac{d\theta}{dt} = 0 \text{ (door starts from rest).}$$

Boundary Conditions:

- Frictional torque is present due to the interaction between the hinges and the door.
- An external torque may be applied intermittently or continuously, representing varying degrees of force exerted on the door.
- The door swings within a confined space, encountering damping forces from the surrounding environment (e.g., air resistance, damping mechanisms in the hinges)

Scenario 1: Free Swing Door

The graph for the free swing door scenario should show a smooth increase in the angle of the door over time, starting from an initial position of 0 radians and gradually swinging freely due to the absence of external torques.

Scenario 2: Pushed Swing Door

The graph for the pushed swing door scenario should exhibit oscillatory behaviour in the angle of the door over time. This oscillation is caused by the sinusoidal external torque applied to the door, simulating someone pushing or pulling it.

Scenario 3: Damped Swing Door

The graph for the damped swing door scenario is expected to show a decaying oscillation in the angle of the door over time. The damping coefficient introduces a damping force that gradually reduces the amplitude of oscillation until the door comes to rest.

IV. SIMULATION ON WOLFRAM MATHEMATICS

1. Defining the Swing Door Model

At the core of our exploration lies the mathematical model capturing the motion of a swing door. The model incorporates parameters such as the door's mass (m), moment of inertia (J), coefficient of friction (μ), and hinge radius (r). These parameters govern the door's angular acceleration and, consequently, its motion over time.

2. Simulating Swing Door Motion

Using the NDSolve function, we simulate the swing door motion for various scenarios, each representing distinct initial conditions and external torque functions. By numerically solving the differential equations governing the swing door dynamics, we obtain trajectories of the door's angular displacement over time.

3. Scenario Analysis

We explore three primary scenarios to study swing door behavior:

Free Swing Scenario: The door swings freely without external torque. This scenario serves as a baseline to observe the door's natural motion.

Pushed Swing Scenario: A constant external force of 10 N is applied at the door's edge, simulating external pushing or pulling. This scenario demonstrates how external forces influence door motion, resulting in oscillatory behavior.

Damped Swing Scenario: Damping effects are introduced by including a damping coefficient in the external torque function. This scenario showcases how damping forces affect the door's motion, leading to a gradual reduction in amplitude over time.

4. Insights and Applications

The Wolfram script facilitates a deeper understanding of swing door dynamics and provides insights

into factors influencing door motion. By manipulating parameters and exploring different scenarios, we gain valuable insights applicable to diverse fields, including architecture, engineering, and robotics.

```
(* Define the swing door model *)
swingDoorModel[{\theta_, \omega_}, t_, {m_, J_, \mu_, r_}, \tau e_] :
    = Module[
        {sign, frictionTorque, totalTorque, \alpha},

        (* Sign function for friction torque *)
        sign = Sign[\omega];

        (* Friction torque *)
        frictionTorque = -\mu m r sign Abs[\omega];

        (* Total torque *)
        totalTorque = \tau e + frictionTorque;

        (* Angular acceleration *)
        \alpha = totalTorque/J;

        (* Return the derivatives of the state vector *)
        {\omega, \alpha}
    ]

(* Simulate door motion for a given scenario *)
simulateDoor[{m_, J_, \mu_, r_}, {\theta0_, \omega0_}, \tau e_, tFinal_, dt_]
    := Module[
        {sol},

        (* Solve the differential equation *)
        sol = NDSolve[
            {
                \theta''[t] =
                = swingDoorModel[{\theta[t], \theta'[t]}, t, {m, J, \mu, r}, \tau e[t]][[2]],
                \theta[0] == \theta0, \theta'[0] == \omega0
            },
            \theta, {t, 0, tFinal},
```

```
MaxSteps -> Infinity,
Method -> "StiffnessSwitching"
];

(* Return the solution *)
\theta /. First[sol]
]

(* Define parameters *)
m = 10; (* kg *)
J = 1.5; (* kg * m^2 *)
\mu = 0.2;
r = 0.1; (* m *)

(* Set initial conditions *)
\theta0 = 0; (* radians *)
\omega0 = 0; (* rad/s *)

(
    * Define external torque functions for each scenario
    *)
    \tau e1[t_] := 0; (* Free swing *)
    \tau e2[t_] := 10; (* Pushed swing with constant force
        *)
    \tau e3[t_] :
    = 5 Sin[2 t] - 0.2 \omega0; (
    * Damped swing with damping coefficient of 0.2 *)

    (* Set simulation parameters *)
    tFinal = 5; (* s *)
    dt = 0.01; (* s *)

    (* Simulate door motion for each scenario *)
    \theta1
    = simulateDoor[{m, J, \mu, r}, {\theta0, \omega0}, \tau e1, tFinal, dt]; (
    * Free swing *)
```

```

θ2
= simulateDoor([m,J,μ,r},{θ0,ω0},τe2,tFinal,dt); (
* Pushed swing *)
θ3
= simulateDoor([m,J,μ,r},{θ0,ω0},τe3,tFinal,dt); (
* Damped swing *)

```

(* Plot the results *)

```

Plot[
{θ1[t],θ2[t],θ3[t]},
{t,0,tFinal},
PlotLegends -
> {"Free Swing","Pushed Swing","Damped Swing"},
FrameLabel -> {"Time (s)","Angle (rad)"},
Frame -> True,
GridLines -> Automatic
]

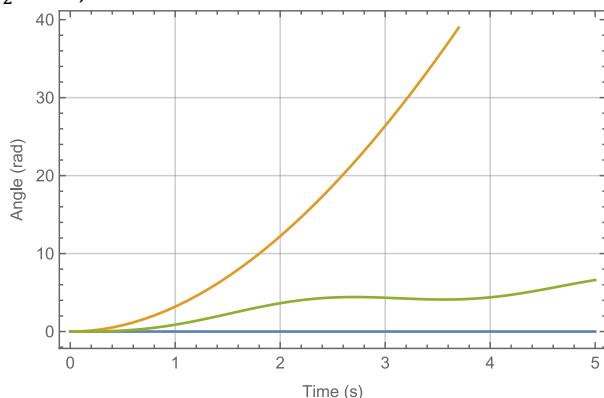
```

Output of Simulation with following parameters

```

m = 10kg,J = 1.5kgm^2,μ = 0.2;
r = 0.1 m
Set initial conditions
θ0 = 0 radians
ω0 = 0 rad/s
Define external torque functions for each scenario
τe1 = 0
Free swing
τe2 = 10;

```



```

m = 10kg,J = 1.5kgm^2,μ = 0.2;
r = 0.1 m
Set initial conditions

```

$\theta_0 = 0$ radians

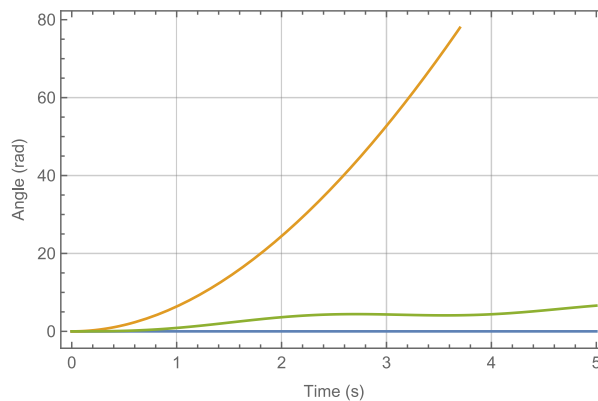
$\omega_0 = 0$ rad/s

Define external torque functions for each scenario

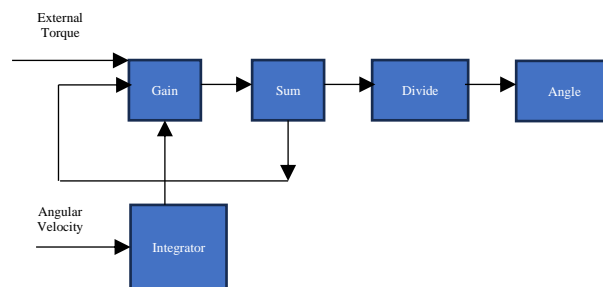
$\tau_{e1} = 0$

Free swing

$\tau_{e2} = 20$;



V. SIMULATION ON MATLAB SIMULINK



Blocks:

1. External Torque Source: This block represents an external torque applied to the system. It will be a source block from the Simulink Sources library. You can choose a specific type of source block depending on your needs, such as a Constant block for a constant torque or a Step block for a sudden change in torque.
2. Gain Block (I): This block multiplies the input signal by a constant value, which in this case

represents the inertia (I) of the system. You can find this block in the Math Operations library.

3. **Sum Block:** This block adds two incoming signals. It's located in the Math Operations library.
4. **Friction Torque Block:** You can represent friction torque in several ways depending on the type of friction involved. Here, it's denoted as " $-\tau_f$ ". You can either use a Constant block with a negative value for constant friction torque or a more complex block like a Coulomb Friction or Viscous Friction block from the Simscape Driveline library if the friction is velocity dependent.
5. **Divide Block:** This block divides the incoming signal by another signal. It's in the Math Operations library.
6. **Integrator Block:** This block integrates the incoming signal with respect to time, essentially calculating the angular velocity. You'll find it in the Continuous library.
7. **Angle Block (Optional):** This block can be used to display or further process the calculated angle based on the integrated velocity. It's located in the Sinks library (optional).

Connections:

- The output of the External Torque Source block connects to the top input of the Sum Block.
- The output of the Gain Block (I) connects to the bottom input of the Sum Block.
- The output of the Sum Block connects to the input of the Divide Block.
- The output of the Integrator Block connects to the input of the Divide Block (denominator).
- The output of the Divide Block connects to the Angle Block (optional) or to another block for further processing.

Setting Block Parameters:

- Set the value of the Gain Block (I) to represent the inertia of your system.
- Adjust the value of the Friction Torque Block according to your friction model.

VI. CONCLUSION

The integration of digital twin technology with conventional doors opens up new possibilities for enhancing the functionality, efficiency, and intelligence of these seemingly mundane objects. By creating digital replicas of doors and simulating their behaviour in various scenarios, we can gain insights into their dynamics, performance, and interactions within smart environments.

Digital twin technology allows us to model the dynamic behaviour of doors in real-time, considering factors such as external forces, friction, and environmental conditions. This enables us to optimize door designs, improve their responsiveness, and predict their behaviour under different circumstances. For example, in Scenario 2, where a door is pushed, a digital twin can simulate the oscillatory motion of the door and help identify optimal strategies for minimizing energy consumption and maximizing user comfort.

Moreover, digital twins can facilitate proactive maintenance and management of doors by monitoring their condition, detecting anomalies, and predicting potential failures. By integrating sensors and IoT devices with digital twins, we can create smart doors that adapt to changing conditions, optimize energy usage, and enhance security.

In conclusion, leveraging digital twin technology for doors offers a paradigm shift in how we perceive and interact with these everyday objects. By creating intelligent, interconnected replicas of doors, we can unlock new levels of efficiency, safety, and user experience in modern smart environments. From optimizing manufacturing processes to

enhancing user convenience in smart homes, the potential applications of digital twins for doors are vast and promising.

V. REFERENCES

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