Particle Swarm Optimization – Based Identification of a Bouncing Spherical Robot

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***Abstract*— In this paper a spherical robot consists of a spherical steel spokes shell and an inner bouncing mechanism. To control the bouncing mechanism, a system model should be introduced. The system model only deal with the first bounce of the spherical mobile robot to overcome the bouncing restitution for landing. This paper presents a transfer function model prediction with particle swarm optimization for a bouncing spherical mobile robot. The particle swarm optimization technique is used in search for accurate model with capability to adapt with different input height of drop. The model is further validated with autocorrelation and cross-correlation test and it is proven to give an error tolerance between the 95% confidence limit.**

Keywords—spherical mobile robot; particle swarm optimization; transfer function model prediction; modeling

I. INTRODUCTION

Mobile robot is widely used in a variety of nonindustrial applications, such as security surveillance, search and rescue, children's education, and entertainment. A spherical robot exhibits a number of advantages with respect to wheeled and legged mechanisms. The spherical rolling mechanism if combined with the power of bouncing mechanism, it will produce excited phenomena. In addition, with spherical rolling mechanisms, the robot can change their direction of motion easier than wheeled mechanisms, and its sphere-shaped do not fall over unlike wheeled and legged mechanisms. Moreover, the general problem of stability of equilibrium that is frequently encountered in mobile robotics is naturally avoided by using spherical rolling. However, there is not much research done on integrating rolling-bouncing and bouncing alone. Most researches are specific into rolling only and the dynamics of spherical rolling systems with bouncing capability can be described by highly complex nonlinear equations, which is difficult to deal with [1 - 6]. Many of the modeling approaches before have come out with mathematical equations which assumptions made that can restrict the actual performance of the nonlinear system. Therefore, an extensive fundamental research on modeling technique to comprehensively represent a sphere rolling that can bounce is been conducted.

II. SPHERICAL ROBOT

A. Sphere Characteristics

A sphere is a unique shape where the set of all points in three-dimensional space lying the same distance – radius, for a given point – center. It can freely rotate about any axis of rotation. In terms of robotics, a spherical structure can freely rotate in any direction and all positions are stable. The shape of sphere provides complete symmetry and a soft, safe and friendly look without any sharp corners or protrusions. The principle of mobility for a sphere is usually based on the movement of its center of gravity (cog) inside the spherical shell. The further the cog is from the center, the greater the driving force that can initiate rolling. The development on ball-shaped object is started as early as 1889 for a simple mechanical toy, but the first prototype and research built for a modern spherical robot only came in 1996 [7]. Current research on the rolling mechanism can be referred to *Omnibola* [8], *SpheRobot* [9], and *OmniQiu* [10].

B. Bouncing Sphere Model

It is a natural phenomenon for an elastic sphere to bounce repeatedly until return to rest after dropped from certain height. For a spherical mobile robot, repeated bounces need to be eliminated as much as possible to ensure a stable landing. This elimination process can be done by experimenting the spherical mobile robot through simulation. By simulating the bouncing, data will be collected in term of height for each bounce. In order to eliminate the bounces, the first bounce is vital. From the first bounce, contact force can be obtained [11]. The internal driving unit of the spherical robot will be designed to encounter the contact force thus will land the robot safely. The first bounce motion of the bouncing spherical mobile robot shown in Figure 1, where h_0 is initial height of drop and h_1 is peak height of first bounce.

C. *Design and Configuration of Spherical Mobile Robot*

The bouncing spherical mobile robot considered in this study is designed based on pull and release mechanism to excite the steel spokes as in Figure 2. The pull and release mechanism will be modeled to encounter contact force from the first bounce of the landing which is acted as a damper. The specifications of the spherical robot as in Table I.

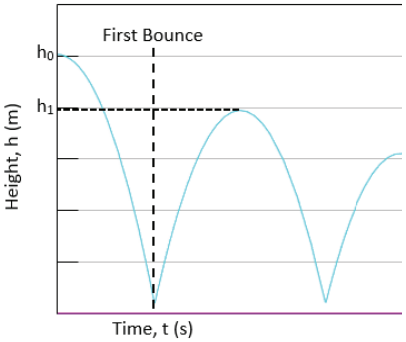

Fig. 1. Height vs time at first bounce

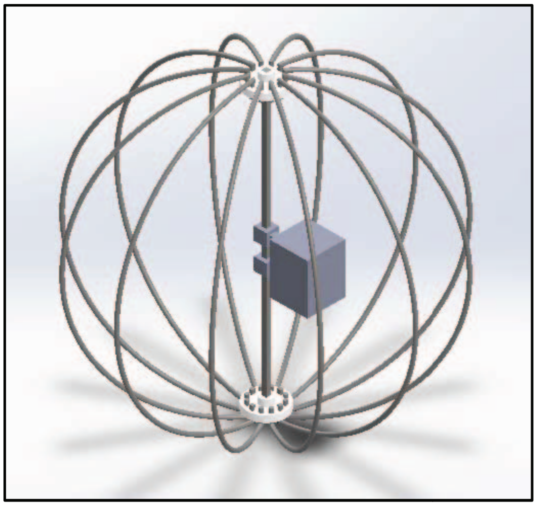

Fig. 2. The proposed design of spherical mobile robot

TABLE I. SPHERICAL MOBILE ROBOT SPECIFICATION

Property	Value
Overall diameter	240 mm
Mass of steel spoke	550 g
Mass of gearbox mechanism	200 g
Mass of battery	143 g
No. of steel spokes	12
Diameter of each steel spoke	4 mm

III. PARTICLE SWARM OPTIMIZATION (PSO)

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995, inspired by social behavior of bird flocking or fish schooling. The system is initialized with a population of random solutions and searches for optima by updating generations. The PSO algorithm is similar to evolutionary computation in producing a random population initially and generating the next population based on current cost, but it does not need reproduction or mutation to produce the next generation. Thus, compared to other evolutionary computation techniques, PSO is faster in finding solutions.

In PSO, the potential solutions, called particles, moving within the search space by following the current optimum particles. Each particle is characterized by its position vector, x and velocity vector, v. The current best coordinates in the problem space is tracked by each particle and stored into particle best, p_{best}. For the highest fitness value of the current iteration, it will be tracked into global best, g_{best}. The particle moves towards their particle best and global best. Their velocity and position are changed according to (1) and (2).

$$v_{i_{new}} = (w \times v_i) + c_1[r_1(p_{best} - x_i)] + c_2[r_2(g_{best} - x_i)] \tag{1}$$

$$x_{i_{new}} = x_i + v_{i_{new}} \tag{2}$$

where c_1 and c_2 are constants known as acceleration coefficients, r_1 and r_2 are two separate random numbers generated uniformly, and w is a known range value known as weight.

The first part of equation (1) provides necessary momentum for particles to move across the search space, represents the previous velocity. The second part, known as cognitive component, encourages the particles to move towards their own best position found so far. The third part is known as social component, represents the collaborative effect of the particles, in finding the global optimal solution. The social always pulls the particles towards the global best particle found so far [12].

By using the equations in PSO algorithm, the objective of the optimization is to find the combination of v and x that give the smallest mean-squared error (*MSE*) of prediction error using the following parameter setting as depicted in Table II.

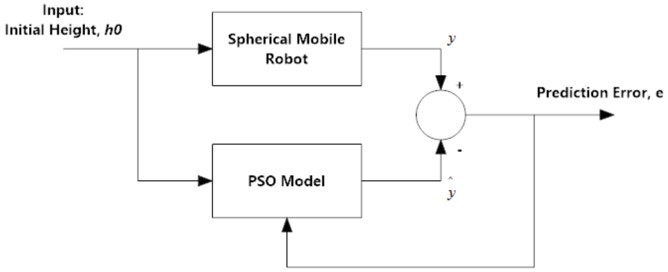

Fig. 3. System identification of the spherical mobile robot based on PSO

The result of the MSE in equation (3) should converge to zero.

$$e(t) = MSE = \frac{1}{N}\sum_{t=1}^{N}|y(t) - \hat{y}(t)|^2 \tag{3}$$

where,

N = Number of denominator

$\hat{y}(t)$ = PSO predicted output

$y(t)$ = Actual output

TABLE II. PSO PARAMETER SETTING

Parameter	Value
Number of iterations	100
Swarm size	50
c_1 , c_2	4
w	[0.4,0.9]

IV. EXPERIMENTAL SETUP

The model use in this experiment is modification of the Bouncing Model example in the MATLAB software as in Figure 3 and Figure 4. The model are fed with the parameter value in Table I.

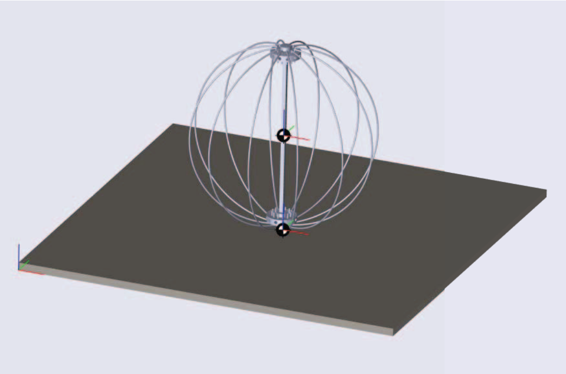

Fig. 4. The SimMechanic Model of Bouncing Spherical Mobile Robot

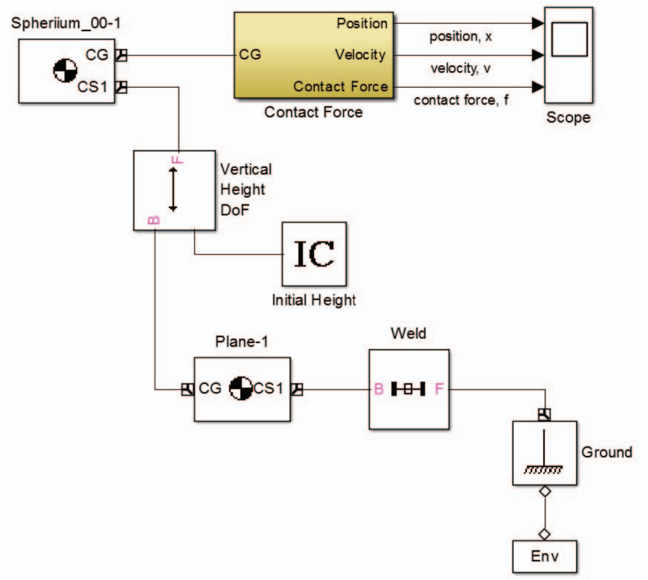

Fig. 5. The Simulink Model of Bouncing Spherical Mobile Robot

The experiment is run by varying the initial height, h_0 from 2.4 m (which is ten times overall diameter of the spherical mobile robot) to 0.0 m with an interval of 0.001 m. This small interval gives the system up to 2400 number of data to ensure that the information are rich in spectral density corresponding to the system bandwidth by exciting all the dynamic modes of interest [13]. The collected experimental simulation data input and output of the system are shown in Figure 6. The data are collected and stored for PSO algorithm process.

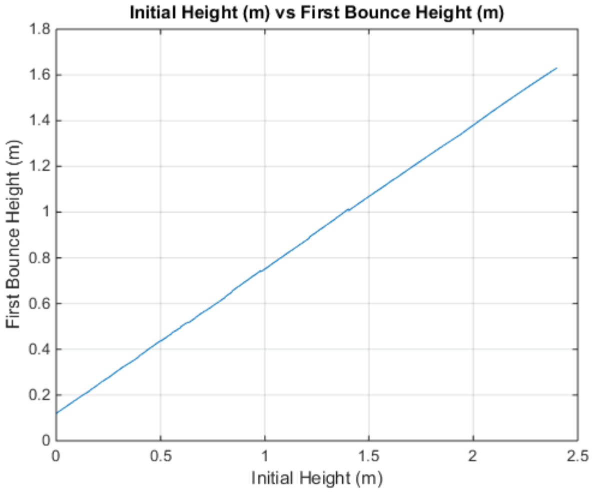

Fig. 6. Collected experimental simulation data input and output of the spherical mobile robot system

V. RESULTS AND DISCUSSION

The MATLAB simulation design for the transfer function in search for the bouncing spherical mobile robot was done using Intel ® Core (iM) i7-4700MQ CPU @ 2.40GHz.

The model transfer function obtained, is given in the z-plane as

$$G(z) = \frac{1.654\,z + 2.63}{z^2 - 0.5785\,z + 0.5934} \tag{4}$$

For the s-plane, the model is:

$$G(s) = \frac{227\,s + 5540}{s^2 + 32.62\,s + 5759} \tag{5}$$

The model system obtained are validated using three methods which are correlation test [14], percentage accuracy and mean-square error. In the correlation test, Figure 7 to 11 shows the results are within 95% of the confidence band. The red lines are the confidence band while the blue lines are the correlation test results. This indicates the model behavior was unbiased and close to that of real system. Figure 12 shows the PSO convergence after 100 iterations. It is clearly shows that the algorithm converge after 50 iterations. Figure 13 shows the mean-squared error value of the predicted model which the best minimum mean-squared error (*MSE*) is 0.0022147. The relatively small *MSE* projects the PSO model is highly accurate to the real system. This can be further shown in Figure 14 where the predicted PSO output trailing the actual output of the system. As addition for the test method, the stability test is done by directly determined from the transfer function obtained in (4) where all zeros and poles must be in the unit circle of z-plane. The open-loop poles of the system are: [-16.3083 +74.1182i, -16.3083 -74.1182i] and the zero located in [24.4087] outside the unit circle indicates the system in unstable. A controller system which will be designed based on the paper will encounter this unstable system obtained.

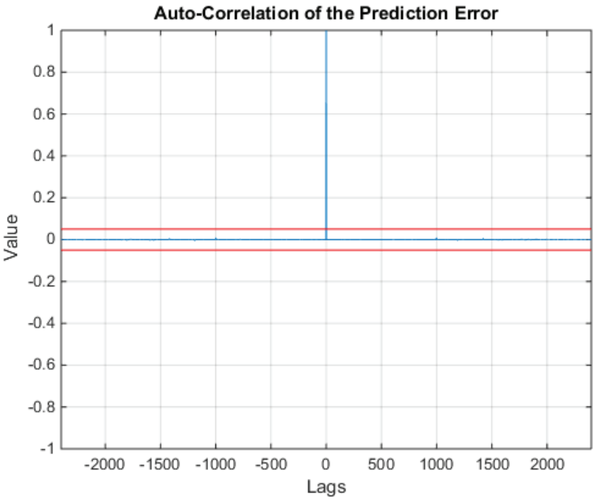

Fig. 7. Auto-correlation of the prediction error

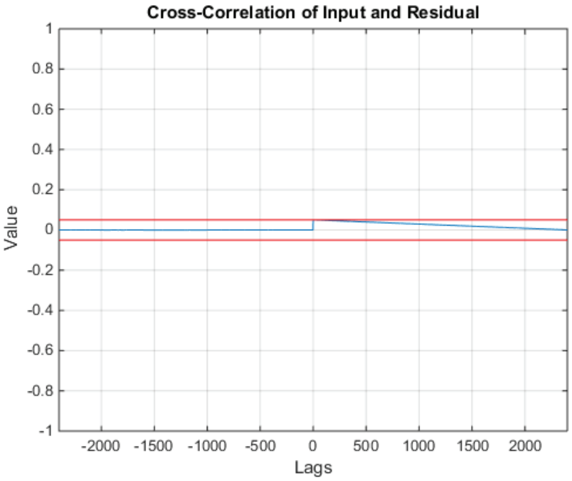

Fig. 8. Cross-correlation of input and residuals

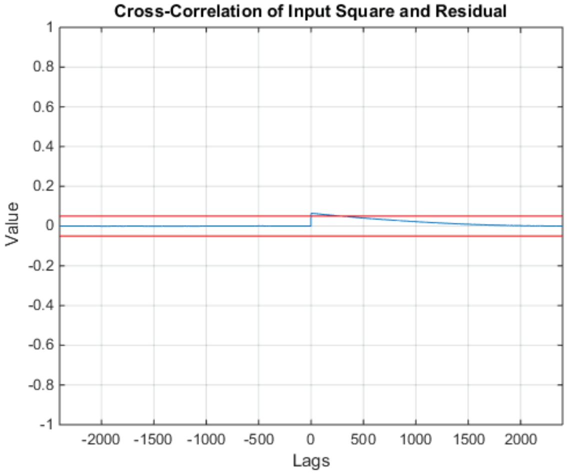

Fig. 9. Cross-correlation of input square and residuals

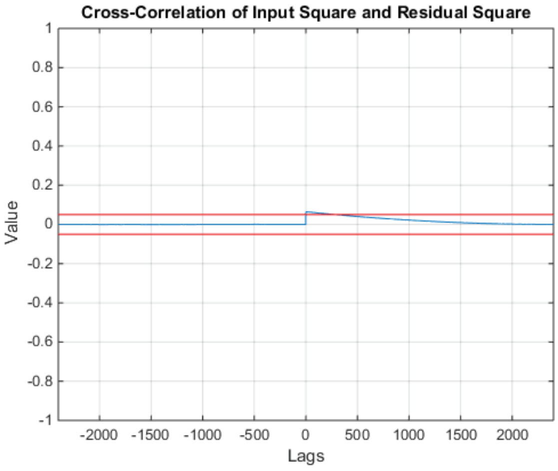

Fig. 10. Cross-correlation of input square and residuals square

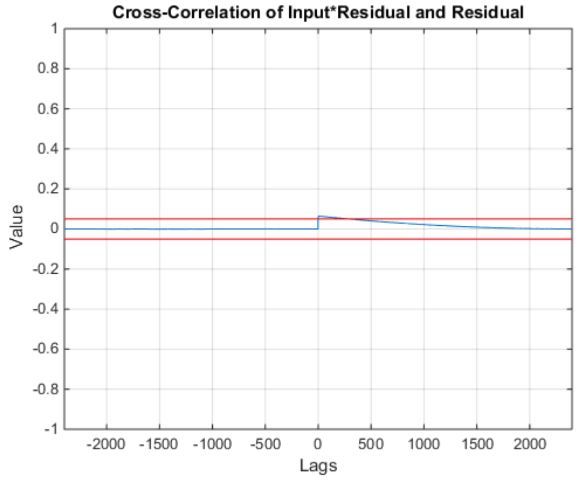

Fig. 11. Cross-correlation of input*residuals and residuals

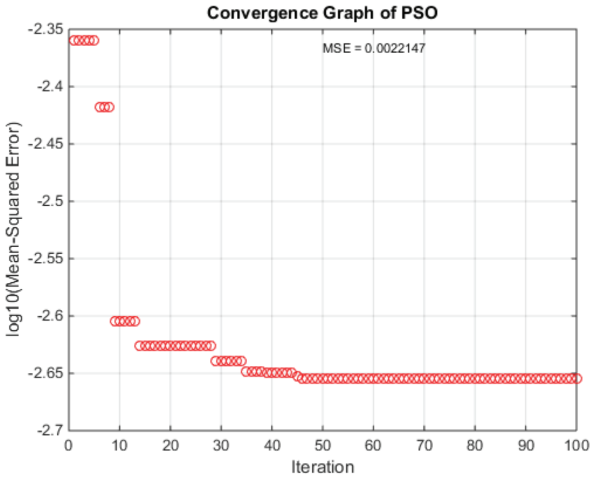

Fig. 12. The Convergence Graph of PSO Algorithm within 100 Iterations

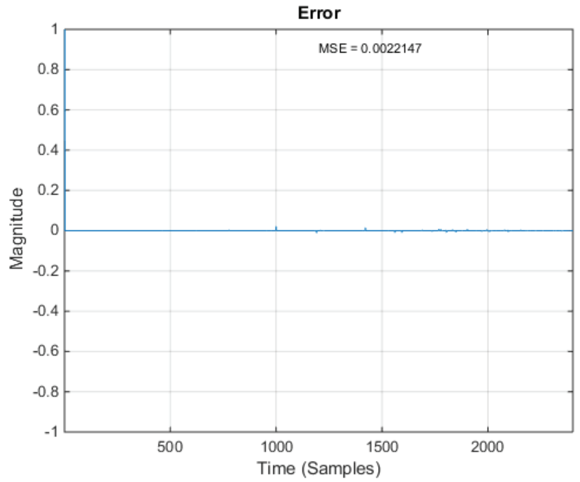

Fig. 13. Mean-Squared Error Value of the Predicted Model

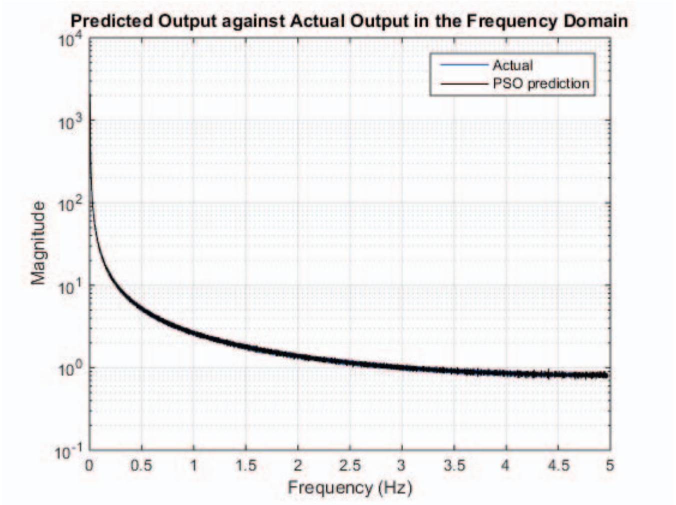

Fig. 14. The PSO predicted output against actual output in the frequency domain

VI. CONCLUSION

The established particle swarm optimization model based algorithm for the transfer function prediction of a bouncing spherical mobile robot configuration has successfully achieved. The accurate model achieved will be extensively used for further investigation for the development of both bouncing mechanism control strategy and rolling mechanism integration.

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