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Reduced Parameter Design Approach to Predict Reliability：A Case Study in A Small-Scale Auto Guided Vehicle

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Keywords：Auto guided vehicle, Reliability, Response surface methodology

ABSTRACT

A new design strategy is applied to multi-target response surface methodology (RSM), the Taguchi method, and dimensional analysis for a small-scale automated guided vehicle (AGV). In the experimental design, four control factors are set to three levels of dimensionless number using the L18 (2^1x3^7) orthogonal table. The new design prototype of the small-scale AGV is constructed using the LEGO EV3 robot system. Optimization analysis of the combined dimensionless parameters reveals that the proposed implementation enhances operational stability. Furthermore, the results can forecast reliability based on vibration values using motor power for streamlined parameter design, serving as a cost-effective substitute for intricate design procedures.

INTRODUCTION

Forklifts are widely used to move cargos in factories, warehouse and offshore wind of construction sites. However, loading and unloading cargo or moving on the rough surface causes the forklift to vibrate, resulting in fatigue or damage to the vehicle (Massone and Boeri, 2010 and Pantazopoulos et al.,2014). Engineers have developed various reliability monitoring techniques to attempt to predict machine failure Gangsar et al.(2017). Since the late 1990s, AGVs have been used in industry for both production and service. The main justification for this is because using them can significantly improve manufacturing efficiency. Experimentation-based validation is essential for AGVs. For mobile robot algorithms to ostensibly operate in real-world settings, for instance, testing on actual data is essential for proper performance evaluation. In addition, in response to labor costs and shortages, enterprises in various industries are increasingly turning to auto-guided vehicle (AGV) forklifts (Beinschoba, et al., 2017). In Industry 4.0. Smart factories, AGVs can already replace human operators for many tasks and the outlook for the expanded use of such devices is strong (Joaquín et al., 2000 and Lijun et al., 2021 and Xu et al., 2021). Through appropriate design, vibration is frequently reduced. Vibration testing is done to see how an AGV will react to a certain vibration environment before it is put into operation. The capacity to perform in a vibration environment and fatigue life have recently received a lot of attention (Alexandre, et al., 2016 and Marcin, et al. 2018). However, real-world tests may be difficult and expensive, especially when using groups of robots. Construction of automatic machines and robotics requires a high level of proficiency in mechanics, automated control, and reliability. Recently, the Lego LEGO EV3 robot has been used for testing robotics applications, and many academics are actively using it as a test tool (Gudeloglu, et al, 2012 and Cheng, et al. 2020 and Thi, et al., 2018).

This paper presents a new forklift design strategy to predict vehicle state, integrated the design of experiment (DOE) method into dimensionless parameters to evaluate vehicle reliability via vibration values and optimized moving distances using the mathematically characterized dimensionless number amplitude. To verify optimization results, we also designed the forklift function in a small-scale auto guided vehicle using the LEGO EV3 robot system (Fig.1). Analytical relations provide a better understanding of the effects of different characteristic parameters, such as lift height / Gravity ratio etc. Furthermore, the relation between the vibration values and the motor power of a small-scale AGV is studied by using the reduced parameter design approach. The effectiveness of the suggested paradigm is illustrated

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using a number of experiment examples without the need of detailed design or finite element analysis methods.

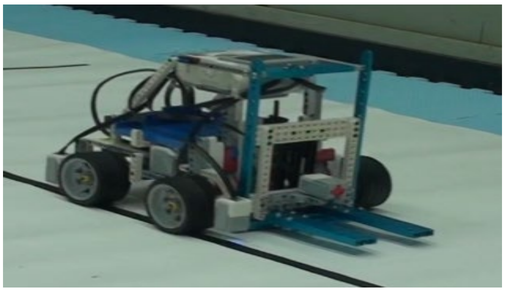

Fig. 1. LEGO EV3 robot-AGV

OVERVIEW OF NEW DESIGN STRATEGY

The response surface methodology (RSM) is used to examine the relationship between a large number of explanatory variables and one or more response variables. The method was first developed by George E. P. Box and K. B. Wilson in 1951. Getting the best answer through a succession of carefully thought-out tests is the fundamental tenet of RSM. Second order regression equations were used to obtain the mathematical equations in this investigation.

$$Y=\alpha_0+\alpha_1X_1+\alpha_2X_2+\alpha_3X_3+\alpha_{11}X_1^2+\alpha_{22}X_2^2+\alpha_{33}X_3^2+\alpha_{12}X_1X_2+\alpha_{13}X_1X_3+\alpha_{23}X_2X_3 \quad (1)$$

where Y denotes the reaction variables of the LEGO EV3 robot-AGV, such as vibration value and working distances. The constant term in this equation is α_0, while the coefficients for the linear and quadratic terms are $\alpha_1,\alpha_2,\alpha_3$ and α_{ij}, respectively. The input variables, Xi, include weight (W_g), motor power (W) and cargo gravity ratio (M_G). In single objective optimization, a solution for one goal may have an unfavorable effect on other output parameters later on in the process. As a consequence, the LEGO EV3 approach was employed to produce effective design parameters through multi-objective optimization. The RSM (Liu et al., 2022 and Isyaka et al, 2021 and Mohammed et al, 2018 and Mohammed et al, 2012) included mathematical programming and a desirability function to optimize control factor values in quality engineering. The output value (yi) is transformed into independence desirability (βi) by using the desirability function. Following that, we determine composite desirability (E) as follows:

$$E=\sqrt[x]{\beta_1\times\beta_2\times\beta_3\times\cdots\beta x}$$

where x stands for the quantity of output values (β). The closer to 1 Composite Desirability(E) is, the better. It ranges from 0 to 1. The Taguchi technique(Peng et al,2022) was used to simplify DOE using an orthogonal array, and the signal-to-noise(S/N) ratio indicates product quality or manufacturing process stability. This approach may efficiently raise product quality with modest quantities of experimental data. A higher S/N ratio represents better production quality. Many problems about experimental size effect can be solved by dimensional analysis (Karimi et al.,2016 and Hua et al.,2020).

The present analysis identifies the main parameters governing changes in performance variables including the relation between the specific lift size of a working material and its weight, motor power according to the mean velocity, the vibration analysis described by using the dimensional analysis. This study considers the stability ratio and dumping safety of AGVs, with the dimensionless number groups from A to D for AGVs given as:

$$A:\frac{\text{Cargo weight}}{\text{Fork weight}} \quad (3)$$

$$B:\frac{\text{Lift height}}{\text{Gravity ratio}} \quad (4)$$

$$C:\frac{\text{Cargo weight}}{\text{Vehicle weight}} \quad (5)$$

$$D:\frac{F\times V}{\text{Motor power}} \quad (6)$$

According to actual working experience, in this experiment, the cargo weight (W_g) is fixed, therefore, equation (7) expresses that vibration value (V) as a function of weight (W_g) motor power (W) and cargo gravity ratio (M_G).

$$V=f(W_g,W,M_G) \quad (7)$$

The SI units of all functions are expressed by mass (M), length (L), and time (T) as follows:

$$V\doteq LT^{-1} \quad (8)$$

$$W_g\doteq M \quad (9)$$

$$W\doteq MLT^{-1} \quad (10)$$

$$M_G\doteq ML \quad (11)$$

According to PI theory

$$\Pi_1=\frac{V}{W_gWM_G} \quad (12)$$

which can be expressed as:

$$\frac{V}{W_gWM_G}=K \quad (13)$$

$$V=KW_gWM_G \quad (14)$$

In the above equations, K is a constant term. The equation can be as:

$$V\overset{(2)}{=}W_g^{a_1}W^{a_2}M_G^{a_3} \quad (15)$$

The dimensionless matrix is given as:

$$\begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & -1 & 0 \end{bmatrix} \times \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix} \quad \begin{matrix} M \\ L \\ T \end{matrix}$$
(16)

After solving, $a_1 = -1, a_2 = 1,\ a_3 = 0$.

Therefore, the dimensionless number can be written by: $V = W_g^{-1} W^1$ (17)

The result is rewritten as

$$V = \frac{W}{W_g} \times K \quad (18)$$

where K is unknown as called characteristic number of the AGV and can be obtained by test. We can easily predict the sensitivity of a similar AGVs for a single dimensionless parameter like K value.

DESIGN EXPERIMENT

We observed that the unmanned truck will cause instability in the handling process due vibration. The paper is concerned with the relation between the vibration values via the power output for a small-scale AGV. We use a wireless transmission vibration recorder combined with the optimized experimental design to observe and record vibration levels, and identify design parameters that provide optimal stability and the vibration value that minimizes impact during the handling process. The results can be used to predict the reliability of a reduced parameter design. The physical profile of the examined AGV is shown in Figs. 2-3, The plastic model measures 374.43 by 223.65 by 224.79 mm, with wheel base of 136 mm, and a tread of 195.65 mm. The cargo lifting part is made of extruded aluminum.

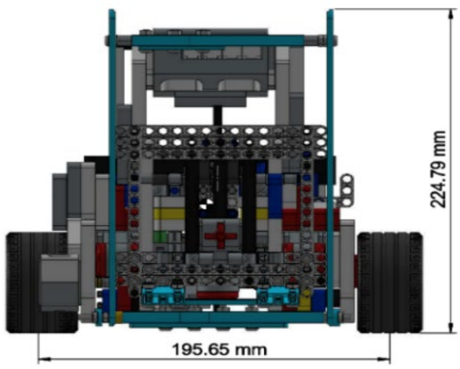

Fig. 2. Right-hand view of the AGV

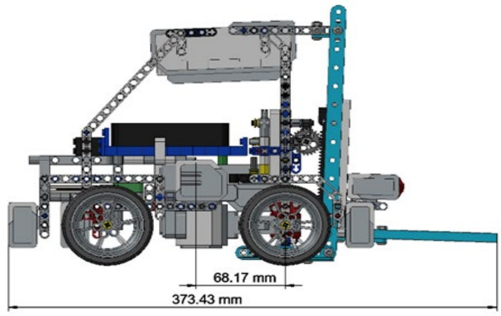

Fig. 3. Front view of the AGV

Parameters of Control Factor

Due to limitations of the experiment field, the moving path is 130 cm, with the forklift traversing the path in 5 minutes, lifting the cargo midway and unloading at the end of the path. The small-scale AGV test site is shown in Fig. 4.

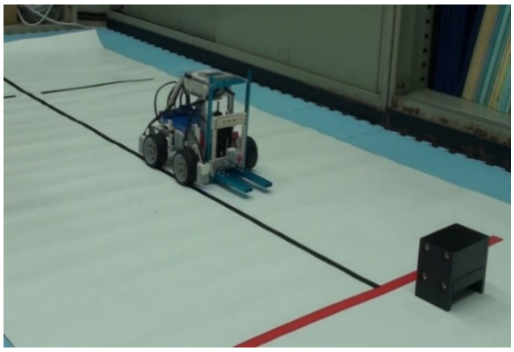
Fig. 4 Small-scale AGV test site

Forks are made using plastic (Fig.5(a)) and extruded aluminum (Fig.5(b)). Motor rotation degrees, vehicle weight, and vehicle motor revolution were chosen as control factors according to the gravity ratio and safe working conditions.

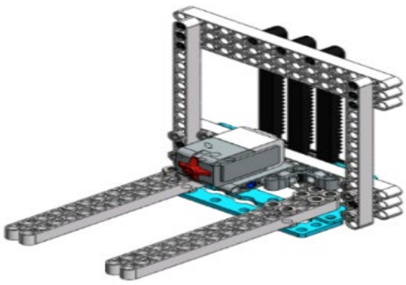
Fig. 5(a) Plastic fork

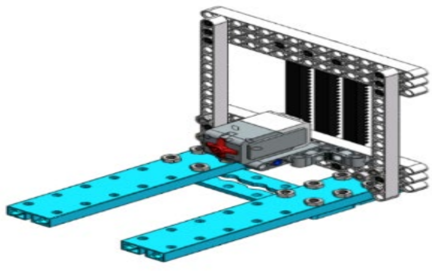

Fig. 5(b) Extruded aluminum fork

Table 1 summarizes the experimental control factors N1: motor rotation degrees, N2: vehicle weight (kg) and N3: vehicle motor revolution (rpm). Motor rotation degrees ranges from 3000 degrees to 6700 degrees due to safety limitations. The net weight of the vehicle is 2.2kg. The total safe weight limitation of the vehicle is 2.6kg. The vehicle motor revolution is between 10 RPM and 30 RPM.

Table 1 AGV control factors

factor	levels		
	-1	0	1
N1: motor rotation degrees	3000	4580	6700
N2: vehicle weight (kg)	2.2	2.4	2.6
N3:vehicle motor revolution (rpm)	10	20	30

Vibration Measuring

Small-scale AGVs were thought to be a good way to quantify vibration in the workplace. The vibration logger measurements (Fig. 6) were taken in the middle location of the small-scale AGV.

Fig. 6 vibration logger

Vibration data analysis settings are shown in Table 2.

Table 2.

Sampling Rate	500 S/s
Analysis Samples	500 S
Analysis points	100
Display	statistical chart
Filter Type	High pass
Cut-Off	100
Analysis	RMS (root mean square)

After RMS has calculated the three axes of X, Y, and Z, the overall average of each axis is made, and the total average vibration value is used as the experimental response value.

Optimization of Multi-Target Response Surface Methodology

The optimized parameters for the plastic and extruded aluminum forks are obtained by multi- target response surface methodology using MINITAB 17 software package, and the vibration value and the working distance at the same motor rotation degrees (3000 degrees) and vehicle weight (2.4 kg) are confirmed by experimentally, as shown in Table 3 and Table 4.

Table 3 Plastic fork optimization compared with experimental results.

	Vehicle motor revolution (rpm)	Vibration	Working distance (cm)
RSM	30	0.018	2997
Experimental results	30	0.021	3296

Table 4 Extruded aluminum fork optimization compared with experimental results.

	Vehicle motor revolution (rpm)	Vibration	Working distance (cm)
RSM	22	0.017	2643.5
Experimental results	22	0.020	2632

According to the analysis of dimensionless number, factor A (Cargo weight/Fork weight), factors B(Lift height/Gravity ratio), factors C (Cargo weight/Vehicle weight), and factors D (FxV/Motor power) are set at three levels, as shown in Table 5. The Orthogonal Array (OA) L18 ($2^1 \times 3^7$) was selected for analysis, as shown in Table 6 and Table 7.

Table 5 Experimental factors and levels.

Factor	Level1	Level2	Level3

A	2.45	2	---
B	0.124	0.144	0.185
C	0.1	0.063	0.052
D	4.31	4.70	5.09

Table 6 Vibration value (Y1) experiment of OA.

	A	B	C	D	Y1	S/N
1	1	1	1	1	0.0115	38.79
2	1	2	2	2	0.0159	35.97
3	1	3	3	3	0.0238	32.47
4	1	2	3	3	0.0254	31.90
5	1	3	1	1	0.0134	37.46
6	1	1	2	2	0.0165	35.65
7	1	1	2	3	0.0187	34.56
8	1	2	3	1	0.0151	36.42
9	1	3	1	2	0.0291	30.72
10	2	3	2	1	0.0132	37.59
11	2	1	3	2	0.0172	35.29
12	2	2	1	3	0.0281	31.03
13	2	3	3	2	0.0197	34.11
14	2	1	1	3	0.0186	34.61
15	2	2	2	1	0.0111	39.09
16	2	2	1	2	0.0180	34.89
17	2	3	2	3	0.0260	31.70
18	2	1	3	1	0.0186	34.61

Table 7 Working distance (Y2) experiment of OA.

	A	B	C	D	Y2	S/N
1	1	1	1	1	1430	63.11
2	1	2	2	2	2112	66.49
3	1	3	3	3	2201	66.85
4	1	2	3	3	2632	68.41
5	1	3	1	1	1267	62.06
6	1	1	2	2	2600	68.30
7	1	1	2	3	2990	69.51
8	1	2	3	1	1332	62.49
9	1	3	1	2	1789	65.05
10	2	3	2	1	1254	61.97
11	2	1	3	2	2470	67.85
12	2	2	1	3	2730	68.72
13	2	3	3	2	1202	61.60
14	2	1	1	3	3185	70.06
15	2	2	2	1	1334	62.50
16	2	2	1	2	2180	66.77
17	2	3	2	3	2210	66.89
18	2	1	3	1	1446	63.20

The effective vibration values of each experiment S/N ratio are shown in Table 8 and Fig. 7. The effective working distance values of each experiment S/N ratio are shown in Table 9 and Fig. 8. We rank the factors according to their respective effect. According to the tables and graph, the experimental factor level of vibration value is A1, B1, C2 and D1 and the working distances are A1, B1, C1 and D3.

Table 8 Vibration value experimental S/N ratio factor response table.

	A	B	C	D
Level1	34.88	35.58	34.58	37.33
Level2	34.77	34.88	35.76	34.44
Level3	---	34.01	34.13	32.71
Effect	0.11	1.58	1.63	4.61
Rank	4	3	2	1

Fig. 7 Vibration value experimental S/N ratio factor response graph

Table 9 Working distance experimental S/N ratio factor response table.

	A	B	C	D
Level1	65.81	67.01	65.96	62.55
Level2	65.51	65.90	65.94	66.01
Level3	---	64.07	65.07	68.41
Effect	0.30	2.94	0.89	5.85
Rank	4	2	3	1

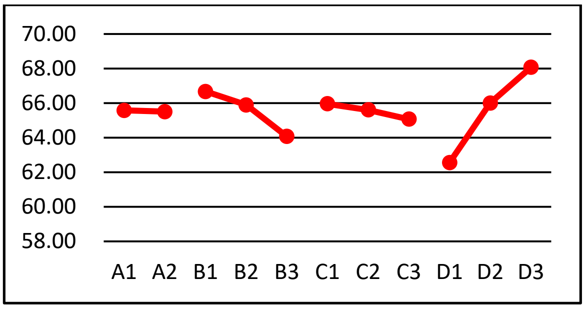

Fig. 8 Working distance experimental S/N ratio factor response graph

According the aforementioned analysis, factor D is the most significant factor, followed by factor A, B and C. The larger the factor D, the higher vibration value; nevertheless, the lower the factor D, the longer working distance. When it comes to the reliability of the small-scale AGVs, we can state that the factor D plays the most important role. When we need to forecast the behavior of a small-scale AGVs, we use measured motor power ratio(D) to build a precise and reliable design using the K value.

RESULTS AND DISCUSSION

The optimized factors are evaluated using the Taguchi method, and the experimental results are shown in Table 10 and 11.

Table 10 Optimal experimental results of vibration values (Y1).

A	B	C	D	Y1	Y2
2.45	0.124	0.063	4.31	0.0093	1454

Table 11 Optimal experimental results of working distance (Y2).

A	B	C	D	Y1	Y2
2.45	0.124	0.1	5.09	0.0182	3055

We use the same conditions to obtain the experimental vibration values, finding that the vibration value of the plastic fork is close to that of extruded aluminum fork when the motor rotation is 3555 degrees, the vehicle weight is 2.6 kg, and the vehicle motor revolution is 13 RPM, as shown in Table 12. According to the Eq. (18), the constant term K is found in the range of 20.8~21.7 as called characteristic number of the AGV. In this scenario, we can even modify the plastic fork into an extruded aluminum fork, the K value for the original design AGVs is a little different, which means that if I offer the appropriate motor output, a robust design can be expected.

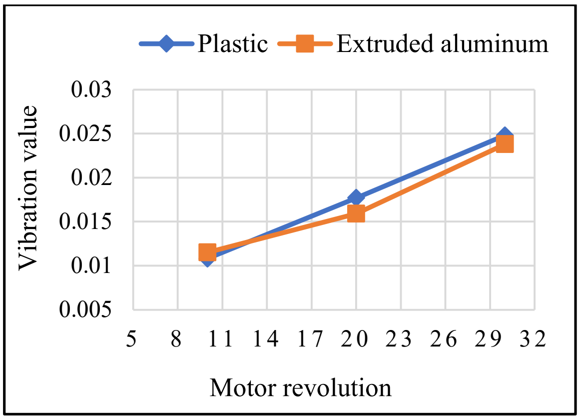

Fig.9 The vibration and motor relationship for plastic and extruded aluminum forks.

CONCLUDING REMARKS

A new design strategy uses the multi-target response surface methodology (RSM) 、the Taguchi method and dimensional analysis to optimize the design of a small-scale auto guided vehicle. Some conclusions can be drawn:

1. ANOVA results for the dimensionless design factors show that the plastic fork outperforms the extruded aluminum fork in terms of vibration value and moving distance.

2. In terms of vibrational properties, this work demonstrates how to apply a dimensionless number strategy to AGVs without using pricey design methodologies.

3. When the vibration value is higher than the anticipated value, we can use it to decide whether the vehicle needs to be stopped and serviced.

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簡化參數設計方法預測可靠性在小尺度無人搬運車個案研究

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摘要

新的設計策略結合多目標反應曲面法(RSM)、田口方法和無因次分析在小型無人搬運車(AGV)研究應用。在實驗設計中，使用 L18(2^1 x 3^7)正交表

將四個控制參數設定為三個無因次數的水準。新設計原型 AGV 是使用樂高 EV3 機器人系統建置完成。經組合無因次數參數的最佳化分析顯示所提出的設計方案可提升運行穩定性。此外，研究結果可藉由使用馬達功率與振動值關係從而預測可靠性，透過簡化參數設計方法可以經濟有效替代複雜的設計程序。