Design and Simulation of Electrostatic Imaging System based on MEMS

Kang Jing-shu, Chen Xi *, Tang Kai, Li Meng-xuan

State Key Laboratory of Mechatronics Engineering and Control, Beijing Institute of Technology, China

chenxi@bit.edu.cn

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Abstract: The electrostatic imaging system obtains the contour profile of charged target by sensing the electrostatic field around. In this paper, a directional electrostatic imaging system is designed based on MEMS technology. Firstly, an electrostatic imaging MEMS sensor is designed on the principle of directional electrostatic induction and the theory of micro electrostatic field sensor. The direction and sensitivity of the sensor are analyzed by using MAXWELL. Secondly, the imaging array is laid by using the directional electrostatic imaging MEMS sensor as the basic unit, and the imaging results of the imaging array is simulated. The simulation result shows that the imaging array composed by the electrostatic imaging MEMS sensor can effectively fulfill the function of imaging the target. It is also proved that the design of electrostatic imaging system based on MEMS is feasible and can improve the imaging resolution effectively compared with the previous system.

1. Introduction

In the detection field, the amount of captured target's information determines the ability of recognition. With the rapid development of information technology, detection with visual image has become an important research direction. Compared with other methods of imaging detection [1~4], electrostatic imaging, which uses electrostatic characteristics of target, has the advantages of good concealment, anti-interference and anti-stealth and it is valuable to research.

Only a few research institutions are engaged in the research of electrostatic imaging technology. University of Sussex in the UK is the mainly research institute abroad, which does non-contact electrostatic imaging research applied to the human body surface [5]. Domestic research institutes mainly include Southeast University and Beijing Institute of Technology. Southeast University realizes the visualization study of the material distribution in industrial process by using the array composed by electrostatic sensor and electrical capacitance tomography (ECT) [6]. Because rotation of electrostatic sensor's electrode and test substance is required during the process, it is considered to be a kind of active electrostatic imaging method. Beijing Institute of Technology studies non-contact electrostatic imaging of ordinary charged target and successfully develops a passive electrostatic imaging principle prototype, which is able to get charged target's contour by verification[7].

In order to improve the electrostatic imaging resolution effectively, system miniaturization is necessary. MEMS technology has the characteristics of miniaturization, integration, high accuracy and microelectronics batch manufacturing, which provides a feasible way for miniaturization of electrostatic imaging system. In the design of micro electrostatic imaging system, miniaturization of the imaging unit is the key point. The imaging unit, which is the electrostatic imaging MEMS sensor designed in the paper, is a kind of miniature electric field sensor with directionality and able to detect electric-field of the target in specific directions. The miniature electric field sensor designed in current studies can be classified as solid type[8] and vibration type[9]. Both of them induce electric-field all round, but vibration type has higher sensitivity, higher consistency and higher stability. In the paper, by adopting the design principle of vibration type miniature electric field sensor and combining the directional command of detection, we proposed two schemes of electrostatic imaging sensor and selected the optimal structure from the perspective of directivity and sensitivity. At last, the imaging array composed by the designed sensor is used to image the target.

2. Overall design of micro electrostatic imaging system

According to the function of the system, micro electrostatic imaging system can be divided into micro imaging array and data acquisition and processing system. Electrostatic imaging array consists of a plurality of electrostatic imaging MEMS sensors. In the array, electrostatic imaging MEMS sensors sense and detect space electric-field of the target, and transform into the electric-field signals into potential signals. Data acquisition and processing system includes hardware equipment and software acquisition system. Its main function is to conduct signal conditioning, A/D conversion and image processing on the potential signals captured by the imaging array, and further convert data to standard gray scale image. The overall design of the system is shown in Fig.1.

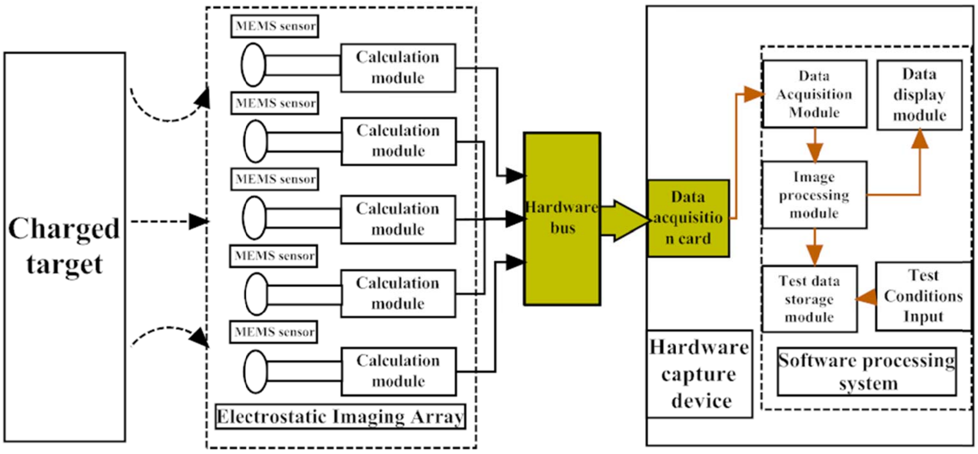


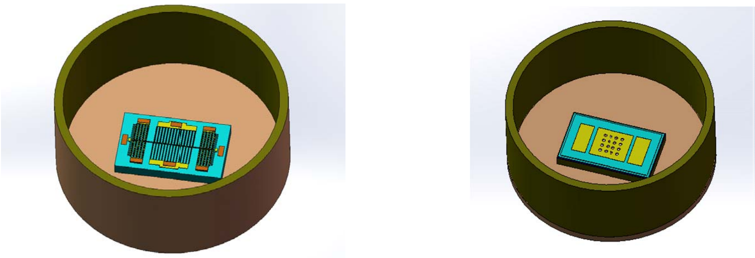
Fig.1 Overall design of electrostatic imaging system

3. Design of electrostatic imaging MEMS sensor

3.1 Design of sensor

By using the directional electric field sensor to get field information of charged target in specific direction[10], we can image the charged target. The conditioning circuit, shielding cylinder and the electrode structure of relative vibration of shielding electrode and induction electrode constitute the electrostatic imaging MEMS sensor. This paper focuses on the analysis of the selection of vibration mode, directivity and sensitivity.

Based on different vibration modes of the shield electrode, we propose two kinds of design schemes, which are vertical vibration type and transverse vibration type, shown in Fig.2.



（a）transverse vibration type (b) vertical vibration type

Fig.2 Structure of electrostatic imaging MEMS sensor

How the electrostatic imaging MEMS sensor works is shown in Fig.3. When it works, current signal i output by the induction electrode is input to conditioning circuit, and after operations like I/V conversion, differential amplifier, correlation detection and low pass filter, it transformed into the final potential signal. The minimum measured current in this paper can be 0.1 pA.

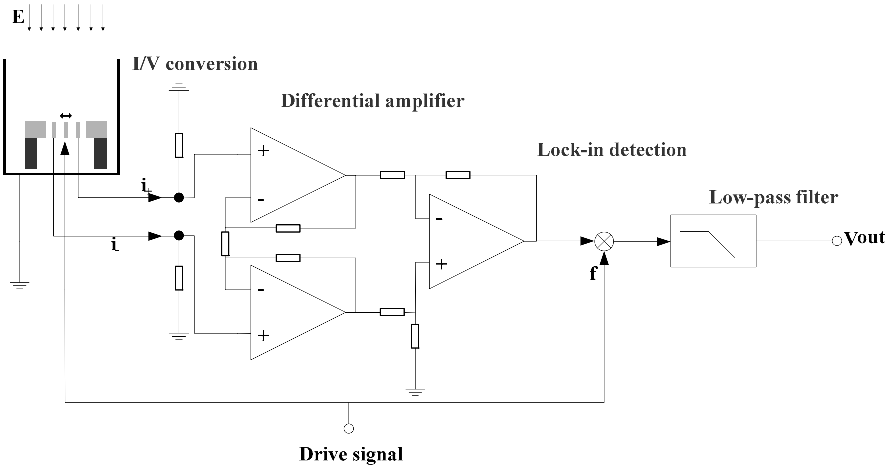


Fig. 3 Principle diagram of of electrostatic imaging MEMS sensor

Taking electrostatic imaging MEMS sensor of vertical vibration type as an example, when the external electric-field is vertical to the sensing electrodes of the sensor, the amount of changed charge in the surface of a single sensing electrode in a cycle is Δq , the total number of induction electrode is n, and the vibration frequency is f , then induced current of the sensor can be approximated as

$$i = \frac{dq}{dt} \approx n \cdot \Delta q \cdot f \quad (1)$$

(1)

After the current is processed by the conditioning circuit which has the equivalent resistance of R_{eq}, output voltage is obtained by

$$V = i \cdot R_{eq} \quad (2)$$

Assuming the measured electric-field magnitude is E, spatial dielectric constant is ε_0, and effective sensing area of sensor is E， then according to the Gauss theorem, the total amount of induced charge of the sensor is obtained by

$$q' = \varepsilon_0 EA \quad (3)$$

Therefore, induced current of the sensor can be expressed as

$$i = \frac{dq'}{dt} = \varepsilon_0 E \frac{dA}{dt} \quad (4)$$

According to Eq.2 and Eq.4, the relationship between the amplitude of measured electric-field and the magnitude of the output voltage of the sensor is deduced as

$$E = \frac{V}{\varepsilon_0 \cdot R_{eq}} \cdot \frac{dt}{dA} \quad (5)$$

Due to periodic vibration of the shielding electrode, $\frac{dA}{dt}$ can be approximately regarded as a constant. So according to Eq.4 and Eq.5, both of magnitude of the induced current and the output voltage of the sensor are proportional to the amplitude of measured electric-field.

3.2 simulation analysis of the sensor performance

Firstly, we simulate the directionality of electrostatic imaging MEMS sensor. Aiming at an infinite homogeneous positively charged plane, electric-field distribution between sensor and a charged planar is shown in Fig.4(the arrow's point expresses the direction of electric-field, the color expresses the size of electric-field magnitude, red represents the maximum value and blue represents the minimum value), which proves that the existence of the grounding shielding cylinder makes only the electric-field lines generated by target's partial parts in front of sensor can enter the sensor, but the electric-field lines are truncated in other directions, which reflects directed detection in part. Meanwhile, the inner wall of shielding cylinder induces a large number of negative charges, which makes part of electric-field lines that straightly point the inside of sensor gradually change direction under the effect of the negative charge, terminate in the shielding cylinder wall and do not reach the induction electrode, thereby greatly reduce the induction efficiency of sensor.

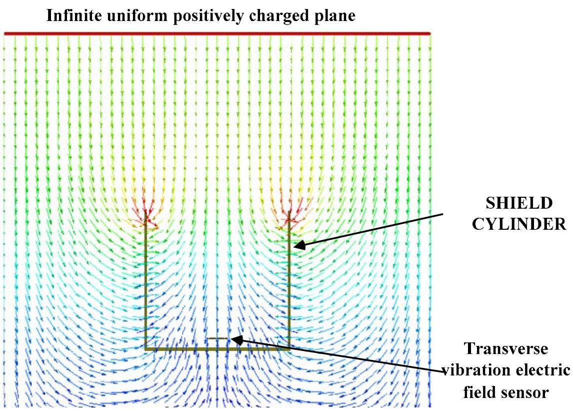


Fig.4 Effect of shielding cylinder to electric-field

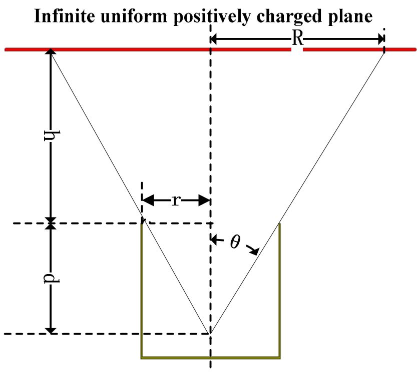


Fig.5 Simulation model of shielding cylinder

Directionality of electrostatic imaging MEMS sensor is determined by the shielding cylinder parameters, which mainly include shielding cylinder radius r and shielding depth d. According to Fig.4, r should be as large as possible in order to avoid distortion of electric-field at the orifice of shielding cylinder. The region size of electrode structure of the sensor is less than 2mm, and r is set to 7mm after many simulations . To study the effect of d on the sensor's directionality, simulation model is established in Fig.5. h is the detection distance, and R is the ideal detectable circle radius when the shielding cylinder makes detection region decrease, then the formula is

$$V = \frac{\sigma}{2\varepsilon_0}\frac{(h+d)}{d}\left(\sqrt{r^2+d^2}-d\right) \tag{6}$$

Considered the effect of grounding shielding cylinder on the electric-field, the real detectable circle radius cannot be calculated accurately by Eq.6.

In the simulation, the detected potential V' is calculated by MAXWELL, the detectable circle radius when the actual situation is simulated can be obtained as

$$R' = \sqrt{\left(\frac{2\varepsilon_0 V'}{\sigma}+h+d\right)^2-(h+d)^2} \tag{7}$$

The quality measurement standard of the directionality of electrostatic imaging MEMS sensor can be expressed by η, which is calculated in Eq.8.

$$\eta = \frac{R'}{R} \tag{8}$$

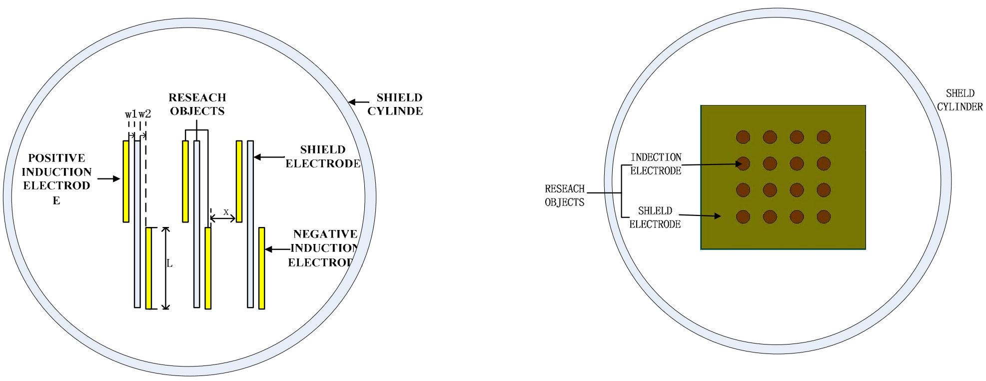
When h=0.1m, $\sigma = 10^{-7} C/m^2$, simulation results are shown in Table 2.

Table 1. simulation result of each sampling point（h=0.1m, $\sigma = 10^{-7} C/m^2$）

d（10^{-3}m）	V′（V）	R（m）	R′（m）	η（%）
1	3.620633	0.703517	0.011396	1.619863
3	2.037101	0.240333	0.008626	3.589155
5	1.080135	0.123667	0.006339	4.308156
7	0.579752	0.106928	0.004687	4.383640
9	0.286889	0.084778	0.003319	3.925003
11	0.129906	0.070665	0.002259	3.197302
13	0.059164	0.060825	0.001538	2.529327
15	0.005592	0.053667	0.000477	0.889074

According to the simulation results shown in Table 2, when shielding cylinder radius r is certain, the larger d is, the smaller V' will be, and the lower induction of electrostatic imaging MEMS sensor will be. When d is 5 to 7mm, η is the largest, the directionality of sensor is the best, but R′ has reduced to almost r, and decreases rapidly with the increase of d. Therefore, considering the directionality, we select d=5mm as the shield cylinder's parameter.

After setting parameters, we select the optimal vibration mode of electrostatic imaging MEMS sensors. Finite element simulation of two kinds of vibration mode is shown in Fig.6



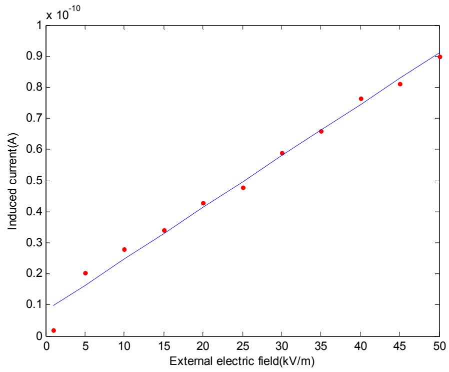
(a) transverse vibration type (b) vertical vibration type

Fig.6 Schematic diagram of local induction simulation

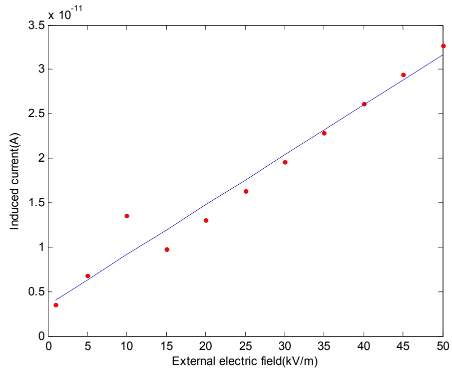
Electrostatic imaging MEMS sensor of transverse vibration type consists of 15 groups of electrodes, and each electrode comprises a shielding electrode and two sensing electrodes. In consideration of symmetry of the simulation structure, we choose three of the 15 groups to simulate and choose one to be the object of the study. By reference to the relevant literature and actual calculation, we set the width between the shielding electrode and the induction electrode as 8μm, the induction electrode spacing as 20μm, and the induction electrode length as 594μm. W1 is the distance between the shielding electrode and the positive induction electrode. When the sensor works, the numerical change of W1 indicates the position change of shielding electrode and the position change of shielding electrode will cause the change of the amount of induced charge Δq. W1 changing from 1μm to 11μm is equivalent to the sensor's 1/2 work cycle.

Different from transverse vibration type, vertical vibration type contains only one group of shielding electrode and sensing electrode. We set the diameter of shielding electrode hole as 0.1mm and the distance between two adjacent holes as 0.2mm, then the size of induction portion is 1mm×1mm. When sensor works, we indicate the position change of the shielding electrode through the numerical changes of W2. When the sensor works, the numerical change of W2 indicates the position change of shielding electrode, the position change of shielding electrode will cause the change of the amount of induced charge Δq . W2 changing from 0. 5μm to 15μm is equivalent to the sensor's 1/2 work cycle.

We set the range of external electric-field as 0~50kV/m and select 11 interval electric-field values to simulate, and the work frequency of both of the sensors is 3.124 kHz. We get the change of induced charge of each sensor Δq in 1/2 cycle by adoption of MAXWELL. According to the Eq.1, the induced current of either sensor is calculated. Then we use fitting method to obtain the variation curve of inducted current with external electric-field shown in figure 7.



(a) transverse vibration type



(b) vertical vibration type

Fig.7 The induced current amplitude curve of the electrostatic imaging MEMS sensor

The induced current is linear with the external electric-field in the two kinds of vibration modes.

Electric-field response rate of transverse vibration type sensor is 1.663×10^{-12}A/(kV/m), and electric-field response rate of vertical vibration type sensor is 1.5625×10^{-13}A/(kV/m). Vertical vibration type has a lower electric-field response rate. It is because the sensitive structure of shield electrode is on a higher layer of the inductive electrode, the charge induction efficiency is low on the induction electrode influenced by the shielding electrode edge effect. Relatively, the transverse vibration sensor uses the unique design of shielding the induction electrode by the side, which reduces the influence of the shielding electrode edge on induction electrode. So we choose transverse vibration type, which has higher rate, as our final design of electrostatic imaging MEMS sensor.

We analyze the sensitivity and accuracy of the transverse vibration type by simulation. According to Fig.7(b), after induction current converts into output voltage through conditioning circuit, the output results still have a linear response with the input electric-field. The response curve is shown in Fig.8. In reference to the design of the sensor[11] and after many simulation calculations, the sensitivity of the sensor is 0.1663mV/(kV/m), the accuracy is 8.54%, which is satisfied with the design requirements of electrostatic imaging MEMS sensor.

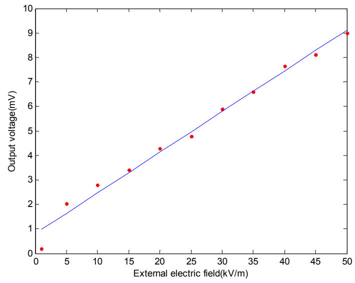


Fig.8 Response curve of electrostatic imaging MEMS sensor

4. Simulation of Electrostatic imaging system

4.1 Layout of imaging array

One single MEMS detection sensor can only obtain partial information of charged target. To achieve complete electrostatic image of target, it requires a plurality of sensors combined in a certain way to collect all target information. At present, imaging array's layouts includes linear, planar and honeycomb. Compared with other layouts, planar array has the advantage of simpler structure and no drive. In adjacency ways of planar array, compared to other kinds of adjacency (such as triangles, hexagon), the advantages of square adjaceny are that each sensor can be corresponding to a pixel point of image, and the imaging effect is intuitive and specific[12]. So we choose the square adjaceny of plane layout to the imaging array. Detection model is shown in Fig.9. Sensors are arranged in matrix, and the interval is 20mm. In Fig.9, i and j represent the row and the column where micro-detection sensor is located in detection array.

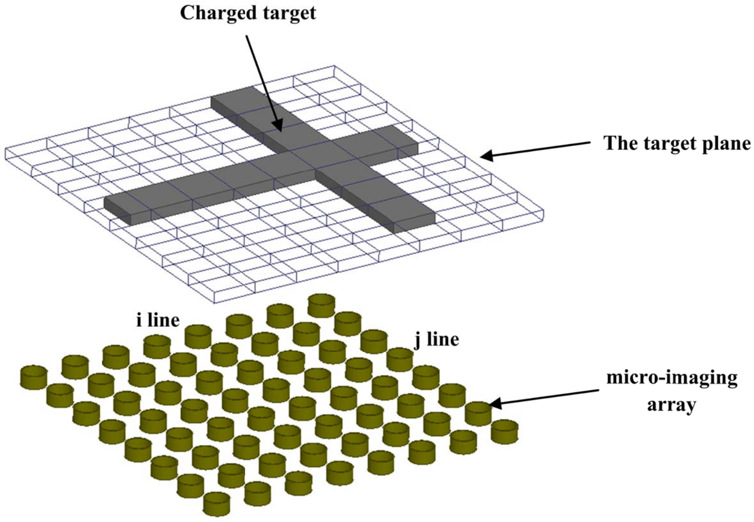
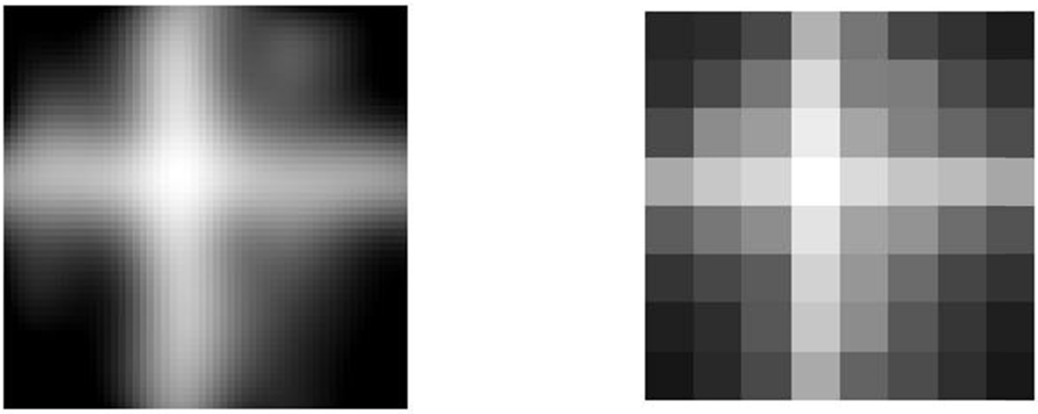


Fig. 9 Model for the detection

4.2 Electrostatic imaging results

We use MAXWELL to simulate the electrostatic imaging array model. When we set the size of electrostatic imaging array 1120mm×1120mm as the standard size, the electrostatic imaging system in this paper has 56×56 pixels, and the simulation results are shown in Fig.10(a).

In order to prove that the design in the paper can improve the imaging resolution, we choose the same size of electrostatic imaging array. The electrostatic imaging system designed in reference [7] has 8×8 pixels, the results of simulation by MAXWELL are shown in Fig.10(b). By comparing Fig.10(a) and (b), the design of electrostatic imaging system based on MEMS has greatly enhanced imaging resolution and has a better imaging effect.



（a）Imaging results of MEMS sensor array　　（b）Imaging results in reference [7]

Fig.10 Grayscale image of charged target

5. Summary

This paper has shown that applying principle of MEMS technology to electrostatic imaging system design can be effective to imaging detection by simulation. Compared with the design in reference [7], this designed system in the paper has advantages of more miniaturization and higher resolution. By further increasing sensitivity of the sensor, the image will be closely matched with the target's charged contour on the whole and the system will have a good applied prospect.

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