THE HVAC MODEL PREDICTIVE CONTROL OF BUILDING THERMAL DYNAMIC CHARACTERISTICS

by

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As the terminal energy user of urban power grid, it is significant to model and simulate the energy consumption characteristics of buildings. First, the author proposes a thermal dynamic model to predict the energy consumption of building refrigeration/heating, it is composed of several groups of heat transient energy balance equations, which can fully consider the impact of heat convection, heat conduction and heat storage on building energy consumption during the heat transfer process of building envelope. Then, the HVAC model predictive control (MPC) method considering the thermal dynamic characteristics of the building envelope is proposed for the heating, ventilation and air conditioning, the core energy unit of the building, the change of window wall ratio in building will affect the thermal insulation performance of the building, so the window wall ratio in building design should not exceed 0.7. From the perspective of building thermal insulation performance, the author analyzes the situation that the total 48 hours operating cost of buildings under two control methods changes due to the change of building thermal insulation performance with the change of window wall ratio in different environments, the simulation results show that when using MPC control method for HVAC, the daily operating cost of buildings increases with the window wall ratio at a lower rate than the traditional control method. It can be seen that the MPC control method has a better effect of energy saving and reducing the total operating cost of buildings in response to the environment where the window wall ratio of buildings increases or the thermal insulation performance of buildings becomes worse over time. It is proved that the HVAC control method based on MPC not only helps to reduce the building energy cost, but also deals with the reduction of HVAC energy efficiency level and the deterioration of building insulation performance, it is more conducive to saving energy and improving the operating economy of buildings.

Key words*: buildings, thermal dynamic characteristics,*
HVAC, predictive control, MPC

Introduction

In recent years, the construction industry has developed rapidly, in 2018, China's total building area was about 601 billion m^2, among them, the urban residential building area is 24.4 billion m^2, the rural residential building area is 22.9 billion m^2, and the public building area is 12.8 billion m^2. The total commercial energy consumption of building operation is 1 billionns of standard coal, accounting for about 22% of the total energy consumption of the country. It

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is estimated that the energy consumption of HVAC system accounts for 40-60% of the total building energy consumption. As the construction of new buildings slows down, the building energy conservation work gradually shifts from the construction design stage to the building operation stage, and it is urgent to improve the energy efficiency level in the building operation stage [1]. At the same time, with the development of air conditioning and new energy technology, complex systems such as cold, heat and power cogeneration, solar air conditioning systems, and ice storage systems have emerged, such systems involve many types of equipment, and the process of system change is relatively complex, reasonable regulation and control methods and strategies are important links to achieve system energy conservation. Therefore, the application of efficient advanced control technology is conducive to building energy conservation and energy efficiency improvement. In addition, 90% of people spend most of their time working and living indoors, with the demand for comfort and health of indoor environment, the control of indoor environment has gradually become localized, personalized and intelligent. According to the research, the indoor environment has a crucial impact on people's quality of life, work efficiency, *etc*. Among them, thermal environment is one of the important factors that affect indoor environmental quality [2]. Therefore, we can make full use of the operating data of the building system and adopt efficient advanced control methods to achieve optimal control of the building system, so as to reduce building energy consumption and improve indoor comfort. As an efficient supervisory control method, MPC has the characteristics of system robustness, good stability, multi-objective rolling optimization, *etc*. It can operate under variable working conditions according to the state parameters, weather parameters, personnel activities and other information of the system to make it meet the indoor comfort. It can dynamically adjust the operating parameters of the system to keep the system in the optimal operating state, thereby reducing the energy consumption of the system.

Literature review

In recent years, a lot of progress has also been made in building HVAC load energy management. As the main energy consumption of building energy supply system, HVAC system accounts for about 33% of the total building energy consumption. The PID controller is used in building HVAC control, but it is difficult to adjust the controller parameters when the external conditions change. The non-linear control method can achieve better control effect, but it requires complex mathematical analysis of the designed non-linear controller to identify its stable state. The robust control method of HVAC can deal with the uncertainties, external disturbances and time-varying parameters of the model, however, because the HVAC system has different conditions in different types of buildings, the robustness of the system is difficult to guarantee. Because of the simplicity and ease of implementation of the rule-based switching control method, it is widely used in HVAC control, however, the HVAC load is adjusted freely according to the upper and lower boundaries of the indoor temperature set by the intelligent building, and no optimization goal is set, in this case, the control mode does not consider the minimization of the building operation cost. Compared with the aforementioned HVAC control methods, the MPC method can use the HVAC simulation model, the thermal dynamic model of intelligent buildings and other prediction models to predict the future operation state (such as indoor temperature), then, by using the advanced optimization algorithm and the set constraints to optimize several objectives, the optimal control action sequence of HVAC can be obtained, the MPC controller is suitable for controlling HVAC using weather and operation information prediction and other available information, which provides a theoretical basis for the author [3]. In fact, building envelope, as a key factor to isolate the direct heat exchange between indoor and outdoor and maintain the indoor hot and humid environment, has a very important impact on HVAC energy consumption, building heat dissipation and heat storage. The MPC is a control algorithm that can be dynamically adjusted in real time. By optimizing the specific objective function in the prediction time domain, the control action of the system at the current time can be obtained, and continuous rolling online optimization can be carried out as time goes by [4].

Building load forecasting model

Building system structure

The structure diagram of the building is shown in fig. 1, including the building, renewable energy power generation unit, MPC controller of HVAC and communication link. Among them, this paper only considers the roof photovoltaic power generation system for renewable energy power generation, and the photovoltaic array is connected to the Building AC bus through the photovoltaic inverter and isolation step-up transformer. The building is equipped with MPC controller that can control the working state of HVAC, as well as existing temperature sensors, controllers, and power load measuring devices [5]. There is a two-way energy flow between the building and the distribution network, and local renewable energy power generation gives priority to the power load demand at the building side. If the energy demand of the building exceeds the total energy provided by the internal power supply of the system, the building will purchase power from the distribution network. If the energy demand of the building does not reach the total energy provided by the internal power supply of the system, the building will feed the excess electricity into the distribution network.

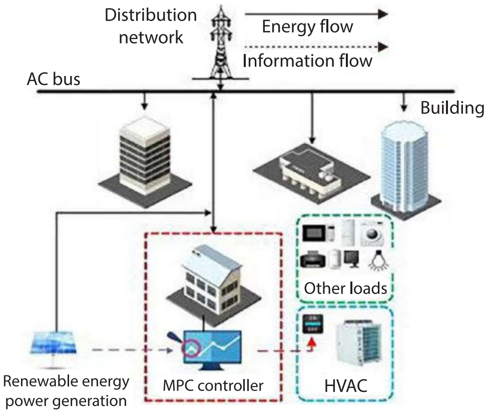

Figure 1. Building system structure

Traditional HVAC control methods

When building HVAC adopts the traditional control method, the HVAC load is automatically adjusted according to the upper and lower boundaries of the indoor temperature set by the building. When HVAC is cooling, it is turned on when the indoor temperature of the building reaches the upper boundary, and turned off when the indoor temperature reaches the lower boundary. When HVAC is heating, it is turned off when the indoor temperature of the building reaches the upper boundary, and turned on when the indoor temperature reaches the lower boundary. The author studies the HVAC control method in the refrigeration environment. When HVAC is enabled (ON), it means cooling, and when HVAC is disabled (OFF), it means stopping cooling. Under the traditional control method, the total load of the building is not controlled, and will be affected by the building use function, normal working hours, users' personal habits, climate change and other factors, the electrical load has strong randomness on the whole [6]. The indoor temperature range of building *i* is set:

$$T_{\text{low}} < T_{\text{room}}^{(i)}(t) < T_{\text{high}} \tag{1}$$

where T_{low} [°C] and T_{high} [°C] are, respectively, the lower and upper temperature limits set for HVAC of building *i*.

Set the current time point as t_k, and use the status identification function describe that HVAC is in the enabled/disabled status, 1 is enabled, and 0 is disabled.

The status identification function of building i in $t_k - t_{k+p}$ period can be expressed:

$$H_k^{(i)}(t) = \begin{Bmatrix} 1, t \in \left[t_k, t_{k+p}\right] \text{ and } t \in t_{\text{work}}^{(i)} \\ 0, t \in \left[t_k, t_{k+p}\right] \text{ and } t \notin t_{\text{work}}^{(i)} \end{Bmatrix} \tag{2}$$

where $t_{\text{work}}^{(i)}$ is the working/oprrating time of building i.

Under the refrigeration environment, the control strategy of building HVAC under the traditional control method can be expressed:

$$\text{control}TRA_k^{(i)}(t) =$$

$$= \begin{cases} 1 \times H_k^{(i)}(t), T_{\text{room}}^{(i)}(t) > T_{\text{high}} \left\| \left(T_{\text{room}}^{(i)}(t) \in \left[T_{low}, T_{\text{high}}\right] \text{ and } \text{control}TRA_k^{(i)}(t-1) = 0 \right) \right. \\ 0 \times H_k^{(i)}(t), T_{\text{room}}^{(i)}(t) < T_{\text{high}} \left\| \left(T_{\text{room}}^{(i)}(t) \in \left[T_{\text{low}}, T_{\text{high}}\right] \text{ and } \text{control}TRA_k^{(i)}(t-1) = 0 \right) \right. \end{cases} \tag{3}$$

$$T_{\text{room}}^{(i)}(t) > T_{\text{high}} \left\| \left(T_{\text{room}}^{(i)}(t) \in \left[T_{\text{low}}, T_{\text{high}}\right] \text{ and } \text{control}TRA_k^{(i)}(t-1) = 0 \right) \right. \tag{4}$$

$$T_{room}^{(i)}(t) < T_{high} \left\| \left(T_{room}^{(i)}(t) \in \left[T_{low}, T_{high}\right] \text{ and } \text{control}TRA_k^{(i)}(t-1) = 0 \right) \right. \tag{5}$$

where $t \in [t_k, t_{k+p}]$.

Building HVAC control method based on MPC

In the building HVAC control method based on MPC, the building prediction model is used to predict the thermodynamic state and the characteristics of electricity and heat consumption of buildings in the future. Then, by optimizing the objective function (that is, the total operating cost of the building), the HVAC control actions at each scheduling moment are obtained. The constraints are HVAC operation constraints and indoor temperature comfort [7].

The author divides the scheduling timeline into uniform time windows, and each time window is the control time domain, the current time point t_k is the starting point of the k^{th} control time domain, and the control action at time t_k is optimized and adjusted according to the prediction results of the t_k, t_{k+p} time domain (*i.e.* the prediction time domain). For the selection of time interval for HVAC control action. On the one hand, in order to avoid damage to its components caused by frequent startup and shutdown of HVAC, the time interval between two control action switching should be greater than 15 minutes. On the other hand, in order to prevent the time interval between the application of control action from being too long, the temperature before the next control action switching exceeds the set upper and lower limits, based on comprehensive consideration, the time interval for applying control actions to HVAC is selected as 30 minutes. For the selection of control time domain: the model proposed by the author obtains the simulation results of each control time domain through simulation enumeration, and optimizes the control actions. If a longer control time domain is adopted, the enumeration results will become more, the simulation time is too long, which increases the complexity of model communication and computing burden. Therefore, the author selects the control time domain as 30min according to the time interval of HVAC control action, and the control time domain is smaller than the prediction time domain [8]. For the selection of prediction time domain: First, in order to avoid the prediction error of the model due to the long prediction time domain. Secondly, due to the slow change of indoor temperature relative to the electrical characteristics, the control scheme is biased to prevent insufficient prediction information caused by short prediction time. Based on comprehensive consideration and the selection of prediction time domain, the author selects the prediction time domain as 12 hours. The specific control process of building HVAC control method based on MPC is:

- *Step 1*. At time point t_k, the indoor temperature measured by the measuring device of the building, the predicted outdoor temperature data for the next 12 hours obtained from the meteorological station, and the light intensity data are used as the input data of the building prediction model.
- *Step 2*. The optimization problem is solved in the prediction time domain (12 hours), and then the control action of HVAC at time point t_k is determined. The actual action of HVAC at time point t_k will follow the optimization results at this time.
- *Step 3*. At time point t_{k+1}, skip to *Step* 1, and continuously scroll along the time axis to obtain control actions at each moment.

For different control systems, the optimization problems solved by t_k at different time points can have different objectives, constraints and control variables. The constraint condition of building *i* is indoor temperature comfort, the control variable is the start and stop of HVAC compressor, corresponding to 1 and 0, respectively, and the objective function is the total operating cost of the building. The building takes the indoor temperature $T_{\text{room}}^{(i)}(t_k)$ at the time of t_k, the outdoor temperature $T_{\text{out}}^{(i)}$ in the next 12 hours and the light intensity as the initial values of its prediction model, the two control actions of HVAC of building *i* in the current prediction time domain (control action ON means cooling, and control action OFF means stopping cooling) can be expressed:

$$\text{control}IMP_k^{ON,(i)}(t)=\begin{cases} 1\times H_k^{(i)}(t), t\in\left[t_k,t_{k+1}\right] \\ \text{control}TRA_k^{(i)}(t), t\in\left[t_{k+1},t_{k+p}\right] \end{cases} \tag{6}$$

$$\text{control}IMP_k^{OFF,(i)}(t)=\begin{cases} 0\times H_k^{(i)}(t), t\in\left[t_k,t_{k+1}\right] \\ \text{control}TRA_k^{(i)}(t), t\in\left[t_{k+1},t_{k+p}\right] \end{cases} \tag{7}$$

where $\text{control}TRA_k^{(i)}(t)$ is the control strategy under the traditional control method of building HVAC. The building thermal dynamic prediction model is used for simulation predict the indoor temperature, *i.e.* $T_{\text{room}}^{(i)}(t_{k+1})$, of the building at t_{k+1} time under two control actions, and the electricity room cost consumption of building i during $t_k - t_{k+p}$ time, so as to determine the optimal control action of HVAC at time point t_k. As the switch operation state of the air conditioner remains unchanged in the control time domain, $T_{\text{room}}^{(i)}(t_{k+1})$ may exceed the temperature constraint. Therefore, the penalty function method is used to transform the constrained problem into the unconstrained problem, and the penalty factor is set:

$$r_k^{(i)}=\begin{cases} 1, T_{\text{room}}^{(i)}\left(t_k+1\right)\in\left[T_{\text{low}},T_{\text{high}}\right] \\ e^{T_{\text{room}}^{(i)}(t_k+1)-T_{\text{high}}}, T_{\text{room}}^{(i)}\left(t_k+1\right)\in\left[T_{\text{high}},+\infty\right] \\ e^{T_{\text{low}}-T_{\text{room}}^{(i)}(t_k+1)}, T_{\text{room}}^{(i)}\left(t_k+1\right)\in\left[-\infty,T_{\text{low}}\right] \end{cases} \tag{8}$$

That is, the electricity consumption with penalty factor is:

$$Cr_{\text{Building},k}^{(i)}=C_{\text{HVAC},k}^{(i)}\cdot r_k^{(i)}+C_{\text{unload},k}^{(i)} \tag{9}$$

where $Cr_{\text{Building}}^{(i)}$ is the power consumption of building *i* with penalty factor within hours, yuan.

Total operating cost of building i with penalty factor:

$$\cos t_k^{(i)} = Cr_{\text{Building},k}^{(i)} - M_{PV_k} \tag{10}$$

where $\text{cos}t_k^{(i)}$ is the total operating cost of building i with penalty factor, yuan [9].

Results and analysis

Basic data

Example building envelope materials and their thermodynamic parameters, the 15 storey 1056 m^2 residential building is used for simulation, its peak power is 430 kW. The $\rho_{\text{air}} = 1.225$ kg/m^3, $c_{\text{air}} = 1005.4$ J/kg°C. The residential electricity price is 0.55 yuan/(kWh), and the temperature range is 24.5~25.5 °C under the cooling scenario in summer. The average heat dissipation of human body, $\text{body}_{\text{per}}^{(i)}$ is 43.84 W, and the heat dissipation ratio of equipment ε is 0.2. The control time domain is 30 minutes, and the prediction time domain is 12 hours. The example scenario selects two consecutive typical days in summer in northern China, and considers the building control method of thermal dynamic characteristics under the refrigeration scenario [10]. The outdoor temperature of photovoltaic active power output is shown in fig. 2.

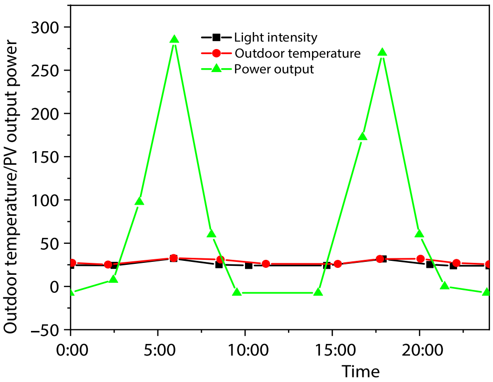

Figure 2. Curve of PV active power output, outdoor temperature and light intensity

Comparison of results of two control methods under different energy efficiency levels

According to the different EER of HVAC, it can be divided into three energy efficiency levels, of which the highest level means the best energy saving effect and the lowest Level 3. The author compares and analyzes the total operating cost of buildings in 48 hours under two control methods for HVAC under different energy efficiency levels, and the change of the increase rate of total building consumption with the decrease of energy efficiency levels, the results are shown in tab. 1 and fig. 3.

Table 1. Comparison of total operating costs of buildings with different energy efficiency levels under two control methods

Energy efficiency grade	EER numeric value	Total operating cost/RMB	
		Traditional control	MPC control
Grade 1	3.90	4940.7	4870.5
Grade 2	3.55	5182.2	5104.2
Grade 3	3.20	5476.6	5389.0

The results in tab. 1 show that under different energy efficiency levels, MPC control method for HVAC can effectively reduce the total operating cost of buildings compared with traditional methods. The results in fig. 3 show that the operating cost of buildings under the traditional HVAC control method increases with the reduction of energy efficiency level, and the growth rate is faster and faster. However, the building operation cost under the MPC based HVAC control method increases at a lower rate than that under the traditional method as the energy efficiency level decreases. It can be seen that the MPC control method can reduce the level of energy efficiency, or the situation that the EER of HVAC equipment is reduced due to no maintenance all the year round has a better effect of saving energy and reducing the total cost of building operation [11].

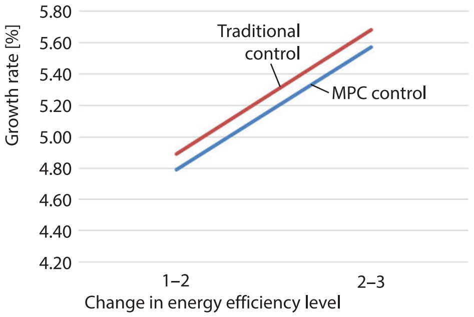

Figure 3. Growth rate of total operating cost of buildings under two control methods of different energy efficiency levels

Comparison of results of two control methods under different window wall ratios

The change of window wall ratio in building will affect the thermal insulation performance of the building, so the window wall ratio in building design should not exceed 0.7. From the perspective of thermal insulation performance of buildings, the author analyzes the situation that the total 48 hours operating cost of buildings under two control methods changes due to the change of thermal insulation performance of buildings with different window wall ratio environments, as shown in tab. 2 and fig. 4. Table 2 shows that when the thermal insulation performance of buildings decreases with the increase of window wall ratio, the operating costs of buildings under the MPC based HVAC control method are lower than those under the traditional control method. The results in fig. 4 show that when using MPC control method for HVAC, the daily operating cost of buildings increases with the window wall ratio at a lower rate than that of traditional control methods. It can be seen that the MPC control method has a better effect of energy saving and reducing the total operating cost of buildings in response to the environment where the window wall ratio of buildings increases or the thermal insulation performance of buildings becomes worse over time [12-15].

Table 2. Total operating costs of buildings with different window wall ratios under two control methods

Window wall than	Total operating cost/RMB	
	Traditional control	MPC control
0.3	4544.9	4523.2
0.4	4879.5	4811.3
0.5	5220.0	5097.2
0.6	5454.7	5306.1

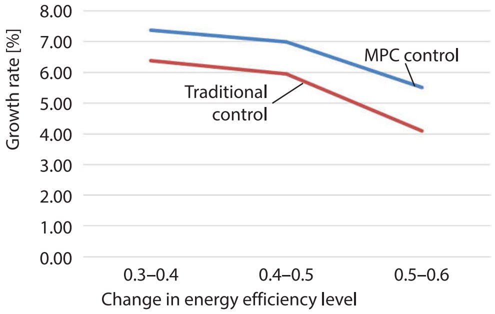

Figure 4. Growth rate of total operating cost of buildings under two control methods with different window wall ratios

Conclusion

The author proposes a building HVAC control method based on MPC, which considers the dynamic thermal characteristics of buildings, the effectiveness of the proposed method is verified by changing the energy efficiency level of HVAC and the window wall ratio of buildings. A building HVAC control method based on MPC is proposed, which can consider the dynamic thermal characteristics of the building, and minimize the energy consumption and operating costs of the building while ensuring user comfort. By changing the energy efficiency level of HVAC equipment for refrigeration/heating source and the window wall ratio of the building, the results of the two building HVAC control methods are compared and analyzed. When the cooling/heating performance of HVAC decreases due to lower energy efficiency level, aging equipment, improper maintenance, or the insulation performance of buildings changes due to changes in window wall ratio or other reasons, the use of MPC based control methods for HVAC is more conducive to energy conservation and consumption reduction. Within a reasonable range, no matter how the EER and window wall ratio change, the total operating cost of the MPC based HVAC control method is lower than that of the traditional control method.

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References

[1] Zeng, T., *et al*., An Adaptive Model Predictive Control Scheme for Energy-Efficient Control of Building HVAC Systems, *Journal of Engineering for Sustainable Buildings and Cities*, *5* (2021), 3, 2
[2] Chen, J., *et al*., Non-Linear Model Predictive Control for a Variable Air Volume Air-Conditioning System, *Journal of Refrigeratio*n, *207* (2019), 9, pp. 626-639
[3] Watthewaduge, G., *et al.*, Reluctance Mesh-Based Magnetic Equivalent Circuit Modelling of Switched Reluctance Motors for Static and Dynamic Analysis, *IEEE Transactions on Transportation Electrification*, *3* (2022), 2, 8
[4] Shao, Z., *et al*., Dynamic Solar Concentration Building Skin Design and Photo-Thermal Characteristics Research, *Architectural Practice*, *177* (2019), 3, pp. 603-625
[5] Tang, S., *et al*., Dynamic Modelling and Improvement on Ash Deposition and Thermal-Hydraulic Characteristics in a Waste Heat Boiler of Cement Kiln, *Applied Thermal Engineering: Design, Processes*, *Equipment, Economics*, *4* (2022), Part 2, 213
[6] Juraev, E. T., *et al.*, Thermal Characteristics of a Solar Greenhouse with Heat Accumulators Based on Phase Change Materials, *Applied Solar Energy*, *58* (2022), 1, pp. 95-104
[7] Zhang, J., *et al*., Main Steam Temperature Control of Thermal Power Boiler Based on Dynamic Matrix Control, *Journal of Xi'an Jiaotong University*, *145* (2019), 7, pp. 2178-2191
[8] Zhang, J. J., *et al*., Dynamic Characteristics of Dual Active Bridge Converter Based on Dynamic Matrix Control, *Advanced Technology of Electrical Engineering and Energy*, *58* (2019), 7, 33
[9] Vaiduriyam, A. R., *et al.*, Dynamic and Sound Radiation Characteristics of a Non-Uniformly Heated Isotropic Plate, Noise and Vibration Worldwide, *3* (2022), 4-5, 53
[10] Guo, W., *et al.*, Multivariate Laguerre Function Fractional-Order PID Predictive Control and Its Application in Load Control of Thermal Power Unit, *China Sciencepaper*, *4* (2019), 2, pp. 89-99
[11] Luo, Q., *et al*., Study on the Dynamic Characteristics of Boiler during Fast Load Regulation, *Journal of Engineering for Thermal Energy and Power*, *67* (2019), 2, pp. 101-109
[12] Chuntian, H. E., et al.,Simulation of Dynamic Characteristics of Pantograph-Catenary System, *Machine Building and Automation*, *2* (2019), 1, 98
[13] Sun, F., *et al.*, Dynamic Characteristics and Responses of Tall Building Structures with Double Negative Stiffness Damped Outriggers, International Journal of High-Rise Buildings, *5* (2021), 3, 10
[14] Heyong, S. I., *et al*., Dynamic Characteristics Coupled Thermal and Dynamic Loads for Labyrinth Seal in Ultra-Supercritical Steam Turbine, *Journal of Aerospace Power*, *2* (2019), 3, pp. 44-47
[15] Liu, J., *et al*., Research on Force-Electrical-Thermal Coupling Characteristics of Shape Memory Alloy Actuators, *Foreign Electronic Measurement Technology*, *47* (2019), 8, 99

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