Pneumatic Industrial Manipulator

Factors Affecting Operating Feel and Evaluation Methods

Enterprise Technology White Paper

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Document type: Engineering study, evaluation method and measured prototype data Version: V1.0 Date: 2026-06

This white paper systematically explains the engineering definition, influencing factors, quantitative evaluation methods and mechanical analysis of operating feel for manipulators. The data are from measured results and site commissioning records for AUREK engineering prototypes.
The parameter values for specific projects should be further determined based on the actual working conditions and safety requirements of the customer.

Abstract

During handling, assembly, loading and unloading, a manipulator requires the operator to push, pull, position and release the workpiece directly. For a long time, site personnel have described operating feel subjectively with terms such as light or heavy, smooth or rough, jerky or not, and stable or unstable after stopping. This study treats operating feel not as a purely subjective sensation but as a composite performance determined by operating force, starting force, steady-motion force and post-stop drift, rebound, response delay, joint damping, end-effector inertia, tooling self-weight, compressed-air supply pressure stability, no-load/load pressure-switching logic and ergonomic factors. It can be converted from a subjective description into measurable and comparable engineering indicators. This study uses Jiangsu Aurek Intelligent Technology Co., Ltd.'s manipulator engineering prototype ARK-S01 and site commissioning experience to build an operating-feel evaluation method for design, commissioning and acceptance. Digital push-pull force gauges, pressure sensors, displacement sensors, angle sensors, response-time acquisition and operator subjective scoring are combined to evaluate different loads and working radii and different tooling states quantitatively. A mechanical model, representative calculation examples, test record forms and FMEA risk analysis explains the evaluation process and diagnostic ideas. It should be noted that the parameters, calculation examples and test data listed in the article come from Actual measurement and analysis of ARK-S01 engineering prototype, relevant conclusions have been verified by prototype testing; when facing specific projects, the relevant values should be It will be further verified based on the customer's working conditions and safety requirements, and the long-term performance of the equipment will be evaluated with systematic and periodic test data.

Keywords: manipulator; operating feel; operating force; balance adjustment; end-effector inertia; response delay; ergonomics

; evaluation method

Contents

1. Introduction

Manipulators are widely used for automotive parts, machined components, enclosures and panels, high-temperature workpiece transfer, and assembly loading and unloading. Unlike simple lifting equipment, a manipulator requires the operator to push, pull, position and release the workpiece directly; the equipment assists by removing the effect of gravity while retaining operator control. Operating feel therefore directly Directly affects operating efficiency, positioning accuracy, operator fatigue and on-site safety risks. In actual working conditions, the operating feel Overall operating feel often determines whether equipment is easy to use more directly than a single indicator such as rated load.

The on-site evaluation of the operating feel mostly appeared in subjective language, such as "it feels a bit heavy to push", "there was a pause when starting up", "it feels better after letting go" Floating upward or sinking", "rebounding after stopping", "switching between no-load and load is not natural enough", etc. These descriptions may seem subjective and vague, but This study links each description to a specific measurable quantity: heavy corresponds to excessive operating force; jerky corresponds to excessive starting force or fluctuating running resistance; upward float/downward sink corresponds to pneumatic balance-pressure error; rebound corresponds to gas compressibility and end-effector inertia; and unnatural switching corresponds to pressure transition and response delay. Converting subjective feel into engineering indicators is therefore a prerequisite for design optimization and quality consistency.

Based on the above background, this study focuses on the following issues:

1. Can the operating feel be transformed from a subjective description into a quantifiable and reproducible engineering indicator?
2. What mechanical, pneumatic, control and ergonomic factors will affect the operating feel, and what is the mechanism?
3. How can a common test method evaluate differences in operating feel among prototypes, tooling configurations and load conditions?

4. How to feed the evaluation results back to the cylinder selection, pneumatic circuit adjustment, tooling weight reduction, joint damping matching and operating armrest design? To focus the study, the object is limited to rigid-arm manipulators driven by pneumatic balancing, including floor-mounted, inverted and transfer-mounted configurations. End-effector tooling includes hooks, external grippers, vacuum cups, pneumatic expanding shafts and custom tooling. The study focuses on mechanics and control response during manual operation; it does not address trajectory planning or closed- loop control for fully automatic robots.

Jiangsu Aurek Intelligent Technology Co., Ltd. has extensive experience in the design, manufacture and site application of manipulators. The AUREK R&D team prepared this document and established a repeatable, recordable and comparable evaluation system using engineering prototype ARK-S01 and multiple site conditions. The operating feel evaluation system enables "feel", an indicator that traditionally relies on empirical judgment, to be measured, analyzed and continuously improved. improved. The conclusions have been validated through prototype testing and may be further adjusted for specific operating conditions.

2. Engineering definition of research objects and operating feel

As noted above, the study covers a pneumatically balanced rigid-arm manipulator and its end-effector tooling system. The equipment approximately balances cylinder-output torque against load torque so the workpiece remains in neutral equilibrium in space and the operator need apply only a small Lifting, horizontal movement, positioning and release can be completed with just a little force. The boundaries of the research object include the body arm, main, middle and front joints, Pneumatic balance circuit, control valve group, operating armrest and end-effector tooling, but does not include fully automatic control system.

2.1 Engineering definition of operating feel

Operating feel is defined as the combined performance, under specified load, working radius, travel, compressed-air supply pressure and tooling state, of an operator uses the armrest or tooling handle to make the manipulator start, raise, lower, move horizontally, stop, position, grip and release, integrating the required operating force, response stability, motion continuity, post-stop holding capability and ergonomic comfort. This definition emphasizes four points: first, feel is performance under certain working conditions, and it is meaningless to talk about feel without load, radius and pressure; Secondly, the feel is the expression of the whole process of movement, not a single moment; thirdly, the feel includes both mechanical quantities and ergonomic factors. Fourth, the feel should eventually be measured and evaluated.

2.2 Operation feel is a comprehensive indicator rather than a single indicator

This study believes that the operating feel should not be described only as "light" or "not light", but should be broken down into mechanics, stability, response, dynamics and Ergonomics and other indicators, supplemented by operator subjective evaluation for cross-validation. The engineering significance of each indicator is shown in Table 1.

Table 1 Classification and engineering significance of operating feel indicators

Indicator category	Specific indicators	Engineering significance
Mechanical indicators	Starting force, steady-motion force, peak operating force	Determine whether the equipment is easy to move and whether sticking is present
Stability indicators	Post-stop drift, rebound and pressure fluctuation	Evaluate positioning and holding stability
response metrics	Button response delay, pressure build-up time, action lag	Determine the sensitivity of pneumatic circuit and control
Dynamic indicators	End-effector inertia, joint damping and motion overshoot	Evaluate whether push-pull motion feels floaty or cumbersome
Ergonomics indicators	Armrest height, holding angle, button position, dual hand gesture	Determine the fatigue level of long-term operation
subjective evaluation	Lightness, smoothness, stability, fatigue score	Correlation verification with objective data

3. Analysis of factors affecting operating feel

The operating feel is formed by the superposition of multiple factors, and any one factor alone is not enough to explain on-site feedback. This study will mainly affect The influencing factors are grouped into five areas: pneumatic balancing, mechanical structure, tooling self-weight and end-effector inertia, pneumatic-circuit control and no-load/load switching, and ergonomics. five aspects and explain their impact mechanisms respectively.

3.1 Pneumatic-Balancing Factors

A manipulator provides assistance by approximately balancing cylinder-output torque against load torque. If balance pressure is too low, the operator If the pressure is too high, the equipment will tend to float upward, which will appear as "floating upwards". in reality Key factors affecting pneumatic balancing include proper adjustment of no-load and load pressures, stability of the compressed-air supply pressure, regulator sensitivity, cylinder friction and seal resistance, and the buffering of pressure fluctuations by the air receiver and check valve. Use. Among them, if the pressure transition is not smooth during no-load/load switching, it is easy to have a sudden upward or downward trend, which is an important factor in the hand feel evaluation. The aspects that need to be focused on.

3.2 Mechanical structural factors

The mechanical structure mainly affects starting resistance, running smoothness and stopping stability. The rotation of the main joint, middle joint and front joint Dynamic resistance, the friction state of bearings, pins, bushings and rollers, and whether there is drag on the joint brakes will all be directly reflected in the starting starting force and steady-motion force. Arm-frame stiffness, joint clearance, changes in arm length and torque at different working radii The change in torque will also affect the size and consistency of the force felt by the operator at different positions. In actual working conditions, joint lubrication Insufficient slip, bearing contamination or improper brake clearance are often the common reasons for "hard start-up and sluggish operation". They have been tested in the prototype. Be validated and can be improved through maintenance.

3.3 Tooling Self-Weight and End-Effector Inertia

Tooling is often a major contributor to operating feel. Even when the manipulator itself is well balanced, excessive tooling mass, center-of-gravity offset or high inertia can make the end feel heavy, cause oscillation or rebound, and impair positioning. Custom tooling design must address not only whether it can grip the workpiece, but also tooling self-weight, center-of-gravity location, combined mass and rotational inertia with the workpiece, and how vacuum cups, gripper jaws and pneumatic expanding shafts affect feel differently. For rotating tooling, center-of-gravity changes at 0°, 45° and 90° must also be calculated. Air-hose, vacuum-hose and cable drag also changes end loading during horizontal movement and return, making The feel becomes "heavy" or the return position is "unnatural".

3.4 pneumatic circuit control and no-load/load pressure switching factors

pneumatic circuit control determines whether the action response is natural. Delay between button triggering and cylinder response, matching of valve group diameter and load, Flow-control setting, air-hose length and bending, and the effects of moisture, oil and contaminants in the compressed-air supply on valve sensitivity all Change the operator's perception of the degree of "following the hand". No-load/load pressure switching is the most sensitive link: if the pressure during loading and unloading If the difference is too large or the control logic is unreasonable, an instantaneous impact will occur, manifested as a sudden rise or sink at the moment of placing or picking up the piece. This study builds It is recommended to set up pressure transition and verification logic for the switching process, and incorporate switching shock into response and stability tests.

3.5 Ergonomic factors

Even if the mechanical indicators are good and the armrest position and operating posture are unreasonable, the operator will still think that the equipment is "unusable". In actual working conditions Among them, whether the height of the armrest is close to the comfortable height of the operator's elbow, whether the button can be triggered, lifted and clamped/released in a natural holding posture Whether the button has an anti-accidental touch design, whether the two-hand operation complies with safety logic, whether the operating line of sight is blocked by tooling or workpiece, and The fatigue caused by long-term repeated operations on the wrists and shoulders will significantly affect the subjective evaluation. Therefore, this study believes that ergonomic factors Factors should be included in the evaluation alongside mechanical indicators, and the operator's height, arm span, and operating experience should be recorded during the test to explain the differences between different people. Differences in ratings between members.

4. Quantitative evaluation index system for operating feel

To convert operating feel into measurable engineering indicators, this study establishes a quantitative system comprising operating force, objective indicators such as starting force and steady-motion force, post-stop drift and rebound, response delay and pressure fluctuation, together with associated subjective ratings. The symbols, units and recommended measurement tools are summarized in Table 2.

Table 2 Summary of quantitative indicators of operating feel

indicator	symbol	unit	Recommended measuring tools	Description
Starting force	Fstart	N	Push-pull force gauge	Maximum operating force at the instant motion starts
Steady-motion force	Fcv	N	Push-pull force gauge	Mean operating force over the stable-motion interval
Peak operating force	Fpeak	N	Push-pull force gauge	Maximum force during a motion cycle
Post-stop drift	Dstop	mm	Displacement sensor/laser distance sensor	Displacement during the specified interval after release of the handle
Rebound	R	mm	Displacement Sensor/Video Analysis	Maximum reverse displacement after stopping
response delay	td	ms	data acquisition system	The time from button to action response
pressure fluctuations	ΔP	MPa	pressure sensor	Pressure changes during movement or switching
Equivalent inertia	Jeq	kg·m²	Calculation/test identification	Represents end-effector dynamic burden
joint damping	Bj	N·m·s/rad	Angle sensor + force test	Reflects the smoothness of horizontal rotation
subjective rating	Q	points	score sheet	Recommended 1-5 points or 1-10 points

4.1 Operating-Force Indicator

Operating force is the most direct representation of operating feel: the push or pull force the operator must apply at the armrest. A digital push-pull force gauge records the operating-force time history at the armrest point, from which starting force, steady-motion force and peak operating force are extracted. In general, lower and less-variable operating force makes handling easier and improves feel; however, it must not be so low that the sense of control is lost, which can cause a floaty feel and difficulty positioning.

4.2 Starting Force and Steady-Motion Force

Starting force represents the static friction, brake drag, initial cylinder friction and load imbalance that must be overcome to initiate motion. It is defined as the maximum operating force between the operator beginning to apply force and the end-effector speed reaching a specified threshold:

$$F_{\mathrm{start}} = \max F(t), \quad t \in [\, t_0 \, , t_v \,]$$

where Fstart is starting force, N; F(t) is the operating-force time history; t0 is the instant the operator begins applying force; and tv is the instant the end-effector speed The moment the set threshold is reached.

With excessive starting force, the operator clearly feels that the first push will not move the device or that motion is jerky. Steady-motion force is the mean absolute operating force over the stable-speed interval and indicates the effort required for continuous handling:

$$F_{\mathrm{cv}} = \mathrm{mean}\,|\,F(t)\,|$$

In order to describe the stability during operation, this study also records the force fluctuation coefficient:

$$CV_{\mathrm{F}} = \sigma_{\mathrm{F}} \;/\; \mathrm{mean}\,|\,F(t)\,|$$

where Fcv is steady-motion force, N; σF is the standard deviation of operating force over the steady-motion interval; and CVF is the dimensionless force-fluctuation coefficient. A lower Fcv means less effort during continuous handling; a higher CVF indicates a greater tendency toward jerky motion, stick-slip or binding. Under actual conditions, steady-motion force and its fluctuation coefficient both increase with working radius, as confirmed by measured data from prototype ARK-S01.

verified in the data.

4.3 Post-Stop Drift and Rebound

Post-stop drift measures the workpiece-position change during a specified time after the operator releases the handle. It reflects balance pressure, pneumatic leakage, brake state Stability of state and load center of gravity:

$$D_{\text{stop}} = |x(t_0 + T) - x(t_0)|$$

where Dstop is post-stop drift, mm; x(t0) is position at handle release; and T is the observation period, which may be 3 s, 5 s or 10 s, and fixed in the test plan.

The amount of rebound measures the maximum reverse displacement that occurs within a short period of time after stopping:

$$R = |x_{\text{peak}} - x_{\text{stop}}|$$

In the formula: R is the maximum rebound amount, in mm; xstop is the position at the moment when force application is stopped; xpeak is the maximum reverse displacement after stopping. location.

Excessive post-stop drift affects positioning, assembly and set-down safety. Rebound is associated with gas compressibility, flow-control setting, arm-frame elasticity, tooling inertia and abrupt operator stopping. Excessive rebound may cause the workpiece to strike a locating surface or reduce assembly accuracy. The observation The observation time is uniformly fixed, and the drift and rebound are recorded at the same time to facilitate comparison between different machines.

4.4 Response delay and pressure fluctuation

Response latency measures the time between button triggering and action response, defined as:

$$t_{\text{d}} = t_{\text{response}} - t_{\text{button}}$$

In the formula: td is the response delay, unit ms; tbutton is the button triggering time; tresponse is the set change of pressure, displacement or speed. Threshold moment.

Response delays should be tested separately for raising, lowering, gripping, releasing, switching from no-load to load, and switching from load to no-load. Pressure fluctuation ΔP represents pressure change during movement or switching and can be sampled synchronously by a pressure sensor. Under actual conditions, response delay is usually associated with an excessively long air hose, insufficient valve-flow capacity or inadequate compressed-air supply, whereas excessive pressure fluctuation is often correlated with post-stop drift.

4.5 Correlation between subjective ratings and objective data

Subjective scoring is used to evaluate starting ease, smoothness of movement, stopping stability, natural response, and positioning from the operator's perspective. For comfort and operating fatigue, it is recommended to use a 1-5 point scale (5 points is the best). This study emphasizes that subjective scoring is not a substitute for objective testing; Rather, it is used to verify the correlation between objective indicators and operator experience. When objective indicators (such as starting force, stopping drift) and subjective When the scores show a stable correlation, it means that the evaluation system has good consistency and can be used as a basis for subsequent optimization. Relevance The specific performance will be explained in Section 8 combined with the actual measured data of the ARK-S01 prototype.

5. Mechanical models and calculation methods

In order to explain the causes of various indicators, this study gives several mechanical models. These models are used to reveal the impact mechanism and magnitude relationship, The parameters such as efficiency, friction and inertia have been calibrated based on the actual measurement of the ARK-S01 prototype; when facing the specific selection, it is recommended to calibrate based on this Based on this, complete design parameters are substituted for further calculation.

5.1 Cylinder output force model

The theoretical effective output force of the cylinder can be expressed as:

$$F_c = P \cdot A \cdot \eta$$

In the formula: Fc is the effective output force of the cylinder, unit N; P is the working pressure of the cylinder, unit Pa; A is the effective pressure area of the cylinder, unit area, m²; and η is the combined cylinder-and-transmission efficiency, including seal friction and linkage losses. It should be identified from prototype measurements or estimated from experience.

This formula shows that the cylinder output force is proportional to the pressure, pressure area and overall efficiency. In actual working conditions, η is often significantly smaller than 1. Ignoring efficiency will overestimate the output force; the value of η used in this study has been calibrated based on the actual measurement of the ARK-S01 prototype.

5.2 Moment balance model

Taking the main rotation fulcrum as a reference, a simplified moment balance relationship can be established:

$$P \cdot A \cdot \eta \cdot L_c = W \cdot L_w + M_f + M_i$$

In the formula: Lc is the cylinder force arm, unit m; W is the total weight of workpiece and tooling (W = mg), unit N; Lw is the load center of gravity The horizontal distance to the rotation fulcrum, in m; Mf is the joint friction resistance moment, in N·m; Mi is the dynamic inertia additional moment, in units

N·m。

This formula intuitively illustrates: an increase in load, an increase in working radius, an outward shift of the tooling center of gravity or an increase in joint friction will all increase the required balance pressure or operating force. This is the mechanical reason operating feel deteriorates at a large radius with heavy tooling, as confirmed by prototype measurements.

5.3 Operating Force and Pressure Error

The force felt by the operator at the handrail can be approximately divided by the combined value of the unbalanced moment, friction moment and inertia moment of the system The armrest equivalent arm is obtained by:

$$F_{op} = \Delta M \ / \ L_h$$

where Fop is the operating force applied by the operator, N; and ΔM is the combined system-unbalance, friction and inertia moment. Value, unit N·m; Lh is the equivalent force arm from the handrail action point to the center of rotation, unit m.

If the air pressure deviation causes an unbalanced moment, the unbalanced moment and the required compensation force can be expressed as:

$$\Delta M_p = \Delta P \cdot A \cdot \eta \cdot L_c$$

$$F_{op,p} = \Delta M_p \ / \ L_h$$

where ΔP is pressure-adjustment error, Pa; and Fop,p is the additional operating force caused by that error, N.

The above equation shows that the greater the pressure adjustment error and the shorter the armrest arm, the greater the push-pull force that the operator needs to compensate additionally. This explains It explains why even a small pressure deviation may make the operator feel "floating" or "sinking" obviously. The specific magnitude will be discussed in Section 7. given in.

5.4 End-Effector Equivalent Inertia and Dynamic Effects

The dynamic load at the end can be approximately described by the equivalent moment of inertia:

$$J_{eq} = J_{arm} + \Sigma\, m_i r_i^2$$

where Jeq is end-effector equivalent rotational inertia, kg·m²; Jarm is equivalent arm-frame rotational inertia; and mi is the mass of the tooling, workpiece and attached The i-th mass such as the piece; ri is the distance from the i-th mass to the center of rotation.

Heavier tooling, a more distant center of gravity and a longer arm all increase end-effector inertia. Excessive inertia causes cumbersome starting and difficulty stopping, Overshoot and rebound increase, so tooling's lightweight and inward center of gravity are important directions to improve the dynamic feel.

5.5 Comprehensive scoring model of operating feel

On the basis of each sub-indicator, this study recommends establishing a comprehensive score of operating feel for overall comparison of different solutions:

$$S = w_1 S_F + w_2 S_D + w_3 S_R + w_4 S_T + w_5 S_J + w_6 S_E$$

where S is the composite operating-feel score; SF, SD, SR, ST, SJ and SE are the scores for operating force, post-stop drift, rebound, response delay, Joint smoothness and ergonomics score; w1-w6 are weight coefficients.

The weight coefficient wi is recommended to be determined based on enterprise experience, customer working conditions and safety priorities, and follow the following principles: Safety-related indicators The weight of the target should be higher than the comfort index; the weight of stopping drift and rebound should be increased under heavy load conditions; the positioning should be increased under precision assembly conditions. stability. High-frequency handling should assign greater weights to operating force and fatigue scores. Specific weights may be set using prototype data Further optimization with on-site feedback.

6. Experimental plan and testing process

6.1 Experimental purpose

The test method proposed in this study aims to establish a repeatable, recordable, and comparable operating feel evaluation process that can be used for sample prototype commissioning, comparison of tooling schemes, reference for factory acceptance, customer-site retesting, fault diagnosis and subsequent product optimization.

6.2 Experimental equipment

It is recommended to configure the following test equipment: • Digital push-pull force gauge: The measuring range is selected according to the load, and it is recommended to have data output; • Pressure sensor: Recommended measurement range 0-1.0 MPa; • Displacement sensor or laser rangefinder: used to measure post-stop drift and rebound;

• Angle encoder or angle sensor: used to measure joint rotation and damping; • Data acquisition module: The sampling frequency is recommended to be no less than 50 Hz, and the response test is recommended to be no less than 100 Hz; • High-speed camera or ordinary video: used to assist in analyzing rebound and overshoot; • Operator subjective rating scale: used to cross-validate objective data.

Note: A stopwatch can be used for preliminary testing, but for formal research it is recommended to use a synchronous acquisition system to ensure the corresponding relationship between force, pressure, displacement and time data.

6.3 Experimental working conditions design

In order to cover the typical usage range, this study recommends setting at least the working conditions shown in Table 3, covering no-load, different load proportions, and different Working radius and load/no-load switching.

Table 3 Operational feel test conditions design

Working condition number	Load status	Working radius	height position	tooling status	Description
A1	No load	minimum radius	median	tooling no load	Measure basic resistance
A2	No load	maximum radius	median	tooling no load	Measuring the influence of arm span
B1	Rated load 25%	middle radius	median	Normal gripping	Light load feel
B2	Rated load 50%	middle radius	median	Normal gripping	Common working conditions
B3	Rated load 75%	maximum radius	median	Normal gripping	Heavier working conditions
B4	Close to rated load	maximum radius	high/low	Normal gripping	Extreme reference conditions
C1	load shedding no load	middle radius	Placement	release action	Measuring switching shock
C2	No-load load shedding	Pickup location	Pickup height	Gripping action	Test loading response

Note: The test close to the rated load must be carried out when safety conditions are met, the equipment status is confirmed, and professionals are present; the test values in this table reflect The measured performance of the ARK-S01 prototype under corresponding working conditions and the long-term performance of the equipment should be comprehensively evaluated through systematic and periodic test data.

6.4 Experimental steps

Under each working condition, it is recommended to conduct testing according to the following steps:

1. Check the equipment installation, feet, joints, air pipes, pressure gauges, tooling connections and safety protection status;
2. Record ambient temperature, compressed-air supply pressure, prototype number, tooling number, load mass, working radius and operator information;
3. Adjust the no-load pressure until the manipulator is approximately balanced without a load;
4. Adjust the load pressure until the manipulator is approximately balanced at the standard load;
5. Complete actions such as starting, moving at a constant speed, stopping, holding, rebound observation and load switching under each working condition;
6. It is recommended to repeat each group of working conditions more than 5 times, and 10 times are acceptable for formal research;
7. Acquire operating force, pressure, displacement, angle and time data synchronously;
8. After each group of tests, the operator fills in the subjective score;
9. Analyze the mean, standard deviation, peak value, coefficient of variation and correlation of the data;
10. Provide adjustment suggestions based on the results, such as pressure fine-tuning, throttle valve adjustment, joint maintenance, tooling weight reduction or armrest optimization.

7. Typical Example Analysis

To demonstrate application of the model, this study provides a representative calculation example. Its parameters are taken from measurements of prototype ARK-S01 and Design data; when facing the specific project selection, the measured parameters and design drawings of the corresponding working conditions should be substituted for calculation.

7.1 Example conditions and equilibrium pressure calculation

Suppose the working condition parameters of a certain handling are as follows: workpiece mass m1 = 80 kg, tooling mass m2 = 18 kg, total mass m = 98 kg; load The distance from the center of gravity to the main fulcrum Lw = 1.8 m; cylinder effective force arm Lc = 0.28 m; cylinder bore D = 125 mm; cylinder comprehensive efficiency η = 0.85; joint friction equivalent moment Mf = 45 N·m. From this it can be calculated:

$$A = \pi D^2 / 4 = 3.14 \times 0.125^2 / 4 \approx 0.0123\ \mathrm{m}^2$$

$$W = m g = 98 \times 9.81 \approx 961\ \mathrm{N}$$

$$M_w = W \cdot L_w = 961 \times 1.8 \approx 1730\ \mathrm{N{\cdot}m}$$

$$M_{total} = M_w + M_f = 1730 + 45 = 1775\ \mathrm{N{\cdot}m}$$

$$P = M_{total} / (A \cdot \eta \cdot L_c) = 1775 / (0.0123 \times 0.85 \times 0.28) \approx 0.61\ \mathrm{MPa}$$

Under this working condition, the load balancing pressure is approximately 0.61 MPa, which is within the working range of common industrial compressed air.

7.2 Analysis of typical problems and possible causes

If measured operating force is clearly excessive at the same load, the model indicates possible causes including a tooling center of gravity farther outward than assumed, excessive joint-friction torque, cylinder efficiency below the estimate, large compressed-air supply pressure fluctuation, or no-load/load pressure not adjusted to The appropriate state, or the armrest arm is too short, resulting in an increase in the force felt by the operator. Most of these reasons can be checked one by one through sub-tests. It embodies the idea of transforming subjective feel problems into diagnosable engineering problems.

7.3 Effect of pressure deviation on feel

In order to illustrate the importance of pressure adjustment accuracy, assume that the pressure adjustment deviation ΔP = 0.02 MPa, the cylinder parameters are the same as above, and the armrest is equivalent The moment arm Lh = 1.6 m, then the cylinder torque deviation and additional operating force caused by the pressure deviation are:

$$\Delta M_p = \Delta P \cdot A \cdot \eta \cdot L_c = 20000 \times 0.0123 \times 0.85 \times 0.28 \approx 58.5\ \mathrm{N{\cdot}m}$$

$$F_{op,p} = \Delta M_p / L_h = 58.5 / 1.6 \approx 36.6\ \mathrm{N}$$

Calculations show that even if the pressure deviates by only 0.02 MPa, the operator may feel an additional push and pull force of about 37 N, enough to be It is obviously felt as "floating" or "sinking". Therefore, this study believes that pressure data must be recorded simultaneously in the evaluation of operating feel, rather than just recording Record operator's subjective feedback.

8. Test data record form and evaluation method

This section uses the actual measured data of the AUREK R&D team on the engineering prototype ARK-S01 to explain the data recording and evaluation methods. The following numbers The value is the representative value after 10 repeated tests under each working condition, reflecting the actual performance of ARK-S01 under the corresponding working conditions; in different machine states, Specific values change with tooling, compressed-air supply and operator conditions; engineering applications shall be governed by measured records for the corresponding conditions.

8.1 Operating-Force Test

Table 4 Measured Operating-Force Data (Prototype ARK-S01, Tooling G01, Operator OP-03, Mean of 10 Repetitions)

Load/kg	Radius/mm	Air pressure/MPa	Starting force/N	Uniform force / N	Peak force/N	force fluctuation coefficient
0	1800	0.50	21.8	11.5	27.4	0.08
40	1800	0.56	30.6	17.9	37.2	0.10
80	1800	0.61	38.4	22.6	46.1	0.12
80	2500	0.63	47.2	28.9	57.8	0.15

Measured data show that starting force and steady-motion force both increase with load and working radius, consistent with the moment-balance model; Under the large radius working condition (2500 mm), the force fluctuation coefficient increases from 0.12 to 0.15, indicating that the operation smoothness decreases. The result is "Large radius hand feel deviation" provides a quantitative basis.

8.2 post-stop drift and rebound test

Table 5 post-stop drift and rebound measured data (5 s observation, prototype ARK-S01)

Load/kg	Radius/mm	Height/mm	5 s drift / mm	Maximum springback/mm	preliminary evaluation
0	1800	1000	1.4	2.1	Class A
80	1800	1000	3.3	5.2	Class A-B
80	2500	1500	6.9	9.4	Class B

The measured data shows that post-stop drift and rebound increase with the increase of load and radius, and the most unfavorable working conditions occur in large radius and high altitude. position. Considering gas compressibility and end-effector inertia, additional buffering or speed limiting is recommended for high-inertia tooling, together with Rebound is reduced through throttle optimization.

8.3 Response delay test

Table 6 Measured data of response delay (unit ms, prototype ARK-S01)

action	The pressure change begins	Displacement change begins	reach stability	Is there any impact
rise	96	152	515	None
fall	108	167	543	None
clamp	78	119	298	None
Release (double button)	131	188	357	None
No-load load shedding	142	209	624	slight
load shedding no load	151	224	638	slight

In the measured data, the response delay from button triggering to the beginning of the displacement is approximately 119-224 ms, which is within the acceptable range of the operator. The no-load/load switching action has the slowest response and is accompanied by a slight impact, which is consistent with the judgment in Section 3 that the switching link is the most sensitive; this study It is recommended to add pressure transition logic to the switching process to reduce shock and shorten settling time.

8.4 Correlation between subjective ratings and objective data

In the same test, the operator subjectively rated two typical working conditions on a scale of 1-5, and the results are shown in Table 7.

Table 7 Comparison of subjective ratings (5-point scale, operator OP-03)

Evaluation items	Standard working condition (80 kg, 1800 mm)	Large radius working condition (80 kg, 2500 mm)
Startup ease	4.3	3.4
Smoothness of movement	4.2	3.5
stop stability	4.4	3.3
respond to naturalness	4.1	3.6
Positioning comfort	4.2	3.2
Operation fatigue	4.0	3.1

All subjective scores decreased appreciably under the large-radius condition, consistent with the objective increases in operating force, post-stop drift and rebound under that condition. Objective increase is consistent. In order to further illustrate the correlation between the two, the AUREK R&D team conducted a correlation analysis on the measured data. The results are as follows As shown in Table 8.

Table 8 Correlation analysis results between objective indicators and subjective ratings

Analysis object	Correlation coefficient r	Relationship description
Load mass - starting force	≈ 0.97	Strong positive correlation, the greater the load, the more difficult it is to start.
Working radius — steady-motion force	≈ 0.95	Strong positive correlation; effort increases with radius
Pressure Fluctuations - post-stop drift	≈ 0.88	Positive correlation, the more unstable the pressure, the greater the drift.
Starting force — starting-ease score	≈ −0.93	Negative correlation; greater force feels subjectively heavier
End-effector inertia — stopping overshoot	≈ 0.90	Positive correlation; overshoot increases with inertia

Note: The above correlation coefficient is calculated based on the actual measured data of the ARK-S01 prototype, which reflects the internal consistency of the evaluation system; with the sample size and working condition coverage With the expansion of the scope, the correlation coefficient can be further refined.

This study believes that when objective indicators and subjective ratings show a stable and mechanism-based correlation, it means that the evaluation system is self-consistent. , which can be used to transform the on-site "feel" into trackable engineering indicators.

8.5 Grading evaluation method

For engineering communication, operating feel is classified into Grades A, B, C and D as shown in Table 9. This grading scheme is an internal AUREK evaluation standard for use with project-specific operating conditions and safety requirements; it will be refined as the engineering database grows.

Table 9 Recommendations for grading operating feel

level	Description	Applicable judgment
A	Easy operation, natural response, stable stopping	Can be used as optimization target
B	The operation is acceptable, a few indicators need fine-tuning	Can be used in general handling scenarios
C	Motion can be completed, but effort or drift is evident	Use after commissioning is recommended

level	Description	Applicable judgment
D	Significant starting force, drift or impact	Direct delivery is not recommended and should be rectified

9. FMEA risk analysis

Operational feel issues are often intertwined with safety risks - post-stop drift, rebound, load switching shock and button mis-pressing are not only It affects the experience and may also affect the safety of personnel, equipment and workpiece. To this end, this study takes the form of Failure Mode and Effects Analysis (FMEA). Formula to sort out common hand-feel-related failures, as shown in Table 10. Severity (S), occurrence (O), detection (D) in the table The risk priority number (RPN) is evaluated based on the AUREK field use experience and the ARK-S01 prototype test results, and is based on the number of enterprise failures. The accumulation of data is continuously updated.

Table 10 FMEA risk analysis related to operating feel

failure mode	Potential causes	Effect on Operating Feel/Safety Effect	S	O	D	RPN	Recommended actions
Excessive starting force	Insufficient joint lubrication, bearing contamination or brake drag	Difficult, jerky starting and increased fatigue	6	5	4	120	Check joint resistance and optimize lubrication and brake clearance
Large fluctuation in steady-motion force	Compressed-air supply pressure fluctuation, valve stiction or cylinder friction	Uneven motion and unstable positioning	6	4	5	120	Add pressure recording; check the pressure regulator and compressed-air mass
Upward or downward drift after stopping	Improper no-load/load pressure adjustment	Workpiece displacement and safety risk	8	4	4	128	Establish a pressure-adjustment standard and add post-stop drift testing
Excessive rebound after stopping	High end-effector inertia, flow control set too open or flexible arm structure	Impact during set-down and inaccurate assembly	7	4	5	140	Optimize flow control, reduce tooling inertia and add cushioning
Excessive response delay	Air hose too long, insufficient valve-flow capacity, or inadequate compressed-air supply	Operation lags and cycle time increases	5	5	4	100	Optimize hose length and valve-bank sizing
Shock during no-load/load transition	Excessive pressure difference or unsuitable control logic	Sudden upward or downward motion	9	3	4	108	Define a switching-validation process and optimize pressure transition
Excessive tooling mass	Redundant custom-tooling structure or unsuitable material selection	Heavy operating feel and high inertia	6	6	5	180	Reduce tooling mass and move the center of gravity closer to the connection flange
Air-hose or vacuum-hose drag	Poor hose routing	Heavy horizontal movement and unnatural return	5	6	3	90	Add an energy chain/swivel joint and optimize hose routing
Armrest position unsuitable	Height, angle or distance mismatch	Wrist and shoulder fatigue	5	5	4	100	Redesign armrest position using ergonomic principles
Unintended button actuation	Unclear button layout or no prevention logic	Unintended tooling actuation and safety risk	9	2	4	72	Two-button release, button zoning and additional labels
Moisture or contaminants in compressed air	Inadequate filtration and drainage	Slower valve response and unstable motion	6	5	4	120	Inspect the filter-regulator unit more frequently and establish a drain interval
Insufficient joint damping	Inadequate damping design or high inertia	Floating feel and overshoot during horizontal rotation	6	4	5	120	Add adjustable damping or optimize damping matching

The RPN results identify excessive tooling mass (180), excessive rebound after stopping (140), and post-stop drift (128) as relatively prominent risks. They should receive priority during design and commissioning. FMEA is not only a risk list; it links operating-feel issues to improvement actions and can be used with test record forms to close the loop from problem identification to quantification and improvement validation.

loop.

10. Optimization suggestions and engineering applications

Based on the analysis above, optimization criteria are proposed for the pneumatic system, mechanical structure, tooling and ergonomics as a reference for design and commissioning. Specific values and measures can be refined using prototype data and customer operating conditions.

10.1 pneumatic system optimization

• Optimize the adjustment range and sensitivity of the pressure reducing valve and establish a pressure calibration process; • Size the air receiver and check valve appropriately to buffer pressure fluctuations; • Reduce air-hose pressure drop and match valve-flow capacity to the load; • Add buffering and pressure transition logic to no-load/load switching to reduce switching impact.

10.2 Mechanical structure optimization

• Reduce joint friction, control joint clearance, and optimize brake release status; • Improve boom stiffness to avoid long-term operations at extreme positions; • Perform damping matching for large radius working conditions to suppress drift and overshoot.

10.3 tooling optimization

• Reduce tooling mass and place the center of gravity as close as possible to the connection flange; • Remove unnecessary overhang and optimize air-hose and vacuum-hose routing; • Calculate the changes in the center of gravity at different angles for the flipped tooling; • Add buffer or speed limit design to large inertia tooling.

10.4 Ergonomics optimization

• The height of the armrest should be consistent with the height of the operator’s elbow, and the holding angle should reduce wrist deflection; • The button should be arranged in the natural thumb or finger reach area, and the release action should be designed to prevent accidental touch; • High-frequency operation stations should consider the adaptability of operators of different heights; • The operator's height, arm span and operating experience should be recorded during the test to explain differences in scores.

10.5 Engineering application suggestions

The AUREK R&D team should use a common Operating-Feel Test Record Form in subsequent prototype development, site commissioning and customer acceptance, Record Table", and gradually accumulate the enterprise engineering database under different loads, different tooling and different working conditions. As the data accumulates, evaluation can be The sub-weights, classification thresholds and FMEA parameters are revised to gradually transition the evaluation system from "empirical judgment" to "data-driven" and provide a better a basis for design optimization and quality consistency.

11. Conclusion

The following principal conclusions are drawn regarding operating feel for manipulators:

1. Operating feel is not a subjective, vague or unmeasurable sensation. It is a composite engineering indicator comprising operating force, starting force, steady-motion force, post-stop drift, rebound, response delay, pressure stability, joint damping, end-effector inertia and ergonomic factors, and can be quantified and evaluated.

2. A push-pull force gauge, pressure sensors, displacement sensors, angle sensors, response-time acquisition and a subjective rating form together provide a relatively complete evaluation system. Objective tests identify equipment state; subjective ratings validate operator experience; the two provide mutual corroboration.

3. Pneumatic balance pressure adjustment is a key factor affecting the feel. If the no-load and load pressures deviate from the reasonable range, it will cause floating, downward sink, excessive starting force or post-stop drift. Pressure, load, radius and operating force should therefore be recorded together during prototype commissioning and delivery acceptance.

4. Tooling self-weight and end-effector inertia strongly affect operating feel. Custom tooling design must consider not only whether the tooling can grip the workpiece, but also mass, center of gravity, inertia, air-hose drag and dynamic behavior during rotation.

5. Operating-feel evaluation should be integrated with safety evaluation. Post-stop drift, rebound, load-switching shock and unintended button actuation not only affect user It may also affect the safety of personnel, equipment and workpiece.

6. This study recommends that Jiangsu Aurek Intelligent Technology Co., Ltd. establish a unified "operating feel test record sheet" in the follow-up work, and gradually form an enterprise engineering database, moving operating-feel evaluation from experience to data and supporting design optimization and quality consistency. The formulas, calculation examples, measured data and classification thresholds given in this study are all based on the testing and analysis of the ARK-S01 engineering prototype. When applied to specific projects, the relevant conclusions can be further verified based on the customer's working conditions and safety requirements.

12. Reference test record appendix

For site use, this appendix provides a sample Operating-Feel Test Record Form. The following are measured records from AUREK R&D prototype ARK-S01 and serve as references for record format, evaluation basis and data trends. Customer-site acceptance requires measured records for the corresponding operating conditions.

Appendix A Basic Test Information Record Form

Note: The following are measured data for prototype ARK-S01, tooling G01 and operator OP-03 under typical commissioning conditions. They may be used as references for record format and evaluation basis; factory acceptance for a customer project requires separate acceptance records for the corresponding operating conditions.

Appendix 1 Test Basic Information Record Form

Project	test record	Project	test record
Prototype number	ARK-S01	Tooling number	G01 standard external-gripping tooling
Load mass/kg	0/40/80	Working radius/mm	1800/2500

Project	test record	Project	test record
Compressed-air supply pressure/MPa	0.50–0.63	Ambient temperature/℃	23 ± 2
Operator number	OP-03	Test date	2026-06-09

Appendix B Prototype actual measurement record sheet

Appendix 2 Operating-Force Test Record Form

Load/kg	Radius/mm	Air pressure/MPa	Starting force/N	Uniform force / N	Peak force/N	Remarks
0	1800	0. 50	21. 8	11. 5	27. 4	No-load base resistance, running Smooth
40	1800	0.56	30.6	17.9	37.2	Light load condition, easy to start
80	1800	0.61	38.4	22.6	46.1	Standard load, controllable feel
80	2500	0.63	47.2	28.9	57.8	Large radius, increased force fluctuations

Appendix 3 post-stop drift and Rebound Record Table

Load/kg	Radius/mm	Height/mm	5 s drift / mm	Maximum springback/mm	Is it acceptable?
0	1800	1000	1.4	2.1	Yes, Class A
40	1800	1000	2.2	3.6	Yes, Class A
80	1800	1000	3.3	5.2	Yes, Class A-B
80	2500	1500	6. 9	9. 4	Conditionally acceptable, it is recommended to reply core

Appendix 4 Response Delay Record Form

action	Start of air pressure change / ms	Displacement change start/ms	Reach stability/ms	Is there any impact	Remarks
rise	96	152	515	None	Smooth response
fall	108	167	543	None	Descending speed Controllable
clamp	78	119	298	None	Clamp in time
Release (double button)	131	188	357	None	Two button anti Normal accidental touch
No-load load shedding	142	209	624	slight	Recommended to keep pressure transition
load shedding no load	151	224	638	slight	View after release

action	Start of air pressure change / ms	Displacement change start/ms	Reach stability/ms	Is there any impact	Remarks
					Observe drift

Appendix Table 5 Subjective rating table for operating feel (1-5 points, 5 points is the best)

Evaluation items	1 point	3 points	5 points	score
Startup ease	obviously laborious	acceptable	Light and natural	4.3
Smoothness of movement	Obvious stuck	Occasional fluctuations	Continuously smooth	4.2
stop stability	obvious drift	slight drift	stop stable	4.4
respond to naturalness	Obvious delay	acceptable	Respond promptly	4.1
Positioning comfort	Difficult to align	Can be completed	Easy to locate	4.2
Operation fatigue	Fatigue is obvious	Average	less fatigue	4.0

(Full text ends)

Note: This information is compiled by the Jiangsu Aurek Intelligent Technology Co., Ltd. R&D team. The parameters, calculation examples and test data in this study come from the ARK-S01 engineering sample Actual measurement and analysis of the machine; when facing specific projects, the relevant values should be further verified based on the customer's working conditions and safety requirements.