Delphi Study

Welcome to this Delphi study. We very much appreciate your participation! In the following, you will receive information about the background, preparation and content of our study. Before the actual questionnaire starts, you will be asked to give informed consent. The total questionnaire consists of 33 proposals to review. Completion time is anticipated to be between 60 and 70 minutes. You can complete the survey across multiple sessions if you do not have the time to complete it in one sitting.

Background information:

Coexisting-cooperative-cognitive (Tri-Co) robots are robots that can naturally interact with the working environments, humans, and other robots, autonomously adapt to complex dynamic environments, and work cooperatively; Tri-Co capabilities (TCCs) are their remarkable characteristic. As a representative research object of Tri-Co robots, collaborative robots (cobots) have garnered important attention and found extensive applications. Meanwhile, the World Robot Contest-Tri-Co Robots Challenge- Collaborative Robots has been successfully held for 9 sessions since 2015. During the contest, experts from the competition's expert committee focus on addressing the comprehensive evaluation of TCCs of cobots, a significant yet insufficiently addressed issue. At the same time, existing research on performance evaluation of cobots has not yet established a complete basic performance evaluation index system for the TCCs of cobots. Therefore, we want to attain consensus on what indices should be included in Class I TCCs evaluation index system for cobots, which are defined as basic performance evaluation index system and have a direct quantitative evaluation attribute for evaluating the basic performance of cobots.

Table 1 - Technical parameter evaluation indices.

Name of index	Unit of measurement	Explaination
Degree of freedom	/	This refers to the number of joints in the robot, with each joint capable of independent movement or rotation. The number of degrees of freedom directly impacts the robot's flexibility and the range of positions it can achieve.
Mass	kg	The total weight of the robot, typically measured in kilograms (kg). Mass affects the stability and power consumption of the robot.
Conventional power consumption	w	The average power consumption of the robot under normal operating conditions, measured in watts (W).
Peak power consumption	w	The maximum power consumption of the robot when operating at maximum load or maximum speed, measured in watts (W).
Real load	kg	The maximum working load that the robot can handle, measured in kilograms (kg).
IP level	/	Indicates the dust and water resistance level of the robot, usually represented by an IP code, such as IP67.
Maximum speed of each joint	rad/s	The highest rotational speed each joint can achieve, measured in radians per second (rad/s).
Range of each joint motion	rad	The maximum angle range through which each joint can move or rotate, typically expressed in degrees (°) or radians (rad).
Maximum torque of each joint	N·m	The maximum rotational torque each joint can generate, measured in Newton-meters (N·m).
Absolute positioning accuracy	mm	The positional error of the robot's end effector when it reaches a specified location, measured in millimeters (mm).
Repetitive positioning accuracy	mm	The consistency of the robot's position when reaching the same location multiple times, measured in millimeters (mm).
The arm span of robot	mm	The maximum span of the robot's arm from one side to the other, typically measured in millimeters (mm).
Bed area	m^2	The area of the robot's base, typically expressed in square meters (m^2).
Maximum end-effector linear velocity	m/s	The maximum linear speed the robot's end effector can achieve, measured in meters per second (m/s).

Table 2 - Kinematic and dynamic performance evaluation indices.

Code	Explaination	Analytical formula	Code	Explaination	Analytical formula
x_{11}	The condition number of the Jacobian matrix as an index for evaluating the end effector operation capability of a robot.	$k(\boldsymbol{J})=\frac{\sigma_1}{\sigma_2}$	x_{31}	Condition number of force Jacobian matrix provides a measure of the sensitivity of the robot's response to forces applied.	$k_{\boldsymbol{G}_F}=\frac{\sigma_{\max}(\boldsymbol{G}_F)}{\sigma_{\min}(\boldsymbol{G}_F)}$
x_{12}	Directional manipulability, based on the specific direction required for a task, characterizes the flexibility of a robotic arm in that particular task direction.	$DM=\frac{1}{\boldsymbol{u}(\boldsymbol{J}\boldsymbol{J}^{\mathrm{T}})^{-1}\boldsymbol{u}}$	x_{32}	Condition number of torque Jacobian matrix provides a measure of the sensitivity of the robot's response to torques applied.	$k_{\boldsymbol{G}_M}=\frac{\sigma_{\max}(\boldsymbol{G}_M)}{\sigma_{\min}(\boldsymbol{G}_M)}$
x_{13}	Manipulability provides a comprehensive measure of a robot's ability to move in various directions under a specific configuration and can be used to assess the overall flexibility of the robot.	$\omega=\sqrt{\det(\boldsymbol{J}\boldsymbol{J}^{\mathrm{T}})}$	x_{33}	Performance index for inertial force evaluates how effectively a robot can manage and counteract inertial forces during its operations.	$\eta_{\boldsymbol{G}+\boldsymbol{H}}=\left\Vert\boldsymbol{G}_q^H\right\Vert+\left\Vert\boldsymbol{H}_q^H\right\Vert$
x_{14}	Improved manipulability also provides a comprehensive measure of a robot's ability to move in various directions under a specific configuration and can be used to assess the overall flexibility of the robot.	$M_r=\frac{\sqrt[m]{\det(\boldsymbol{J}\boldsymbol{J}^{\mathrm{T}})}}{f_m}$	x_{41}	Global performance evaluation index for linear velocity evaluates the dexterity of a robot's linear velocity across its entire workspace.	$\eta_{\boldsymbol{G}_v}=\int_\Omega\frac{1}{k_{\boldsymbol{G}_v}}d\Omega\Big/\int_\Omega d\Omega$
x_{15}	The isotropy index is used to measure the isotropy of the manipulability ellipsoid.	$\Delta=m\cdot\frac{\sqrt[m]{\lambda_1\lambda_2\cdots\lambda_m}}{\lambda_1+\lambda_2+\cdots+\lambda_m}$	x_{42}	Global performance evaluation index for angular velocity measures the dexterity of a robot's angular velocity across its entire workspace.	$\eta_{\boldsymbol{G}_\omega}=\int_\Omega\frac{1}{k_{\boldsymbol{G}_\omega}}d\Omega\Big/\int_\Omega d\Omega$
x_{16}	Improved isotropy index is also used to measure the isotropy of the manipulability ellipsoid.	$\Delta'=\frac{\sqrt[m]{\lambda_1\lambda_2\cdots\lambda_m}}{\lambda_1}$	x_{43}	Global performance evaluation index for linear acceleration measures the dexterity of a robot's linear	$\eta_{\boldsymbol{H}_v}=\int_\Omega\frac{1}{k_{\boldsymbol{H}_v}}d\Omega\Big/\int_\Omega d\Omega$

				acceleration across its entire workspace.	
$x21$	The performance index for linear velocity based on influence coefficients evaluates the robot's ability to achieve desired linear velocity.	$k_{\boldsymbol{G}_v} = \lVert \boldsymbol{G}_v \rVert \lVert \boldsymbol{G}_v^{+} \rVert$	$x44$	Global performance evaluation index for angular acceleration measures the dexterity of a robot's angular acceleration across its entire workspace.	$\eta_{\boldsymbol{H}_\omega} = \int_\Omega \frac{1}{k_{\boldsymbol{H}_\omega}} d\Omega / \int_\Omega d\Omega$
$x22$	The performance index for angular velocity based on influence coefficients evaluates the robot's ability to achieve desired angular velocity.	$k_{\boldsymbol{G}_\omega} = \lVert \boldsymbol{G}_\omega \rVert \lVert \boldsymbol{G}_\omega^{+} \rVert$	$x45$	Global performance evaluation index for force measures the dexterity of a robot's forces across its entire workspace.	$\eta_F = \int_\Omega \frac{1}{k_F} d\Omega / \int_\Omega d\Omega$
$x23$	The performance index for linear acceleration based on influence coefficients evaluates the robot's ability to achieve desired linear acceleration.	$k_{\boldsymbol{H}_v} = \lVert \boldsymbol{H}_v \rVert \lVert \boldsymbol{H}_v^{+} \rVert$	$x46$	Global performance evaluation index for torque, measuring the dexterity of a robot's torques across its entire workspace.	$\eta_M = \int_\Omega \frac{1}{k_M} d\Omega / \int_\Omega d\Omega$
$x24$	The performance index for angular acceleration based on influence coefficients evaluates the robot's ability to achieve desired angular acceleration.	$k_{\boldsymbol{H}_\omega} = \lVert \boldsymbol{H}_\omega \rVert \lVert \boldsymbol{H}_\omega^{+} \rVert$			

Preparation:

In the proposals that we will present to you, we have already organised several brainstorming sessions with some experts from the competition's expert committee, aimed at constructing a Class I TCCs evaluation index system. Based on this preliminary set of evaluation indices, we are now soliciting opinions from experts in related fields to gradually reach a consensus and establish the final Class I evaluation index system.

Content:

Within Class I TCCs evaluation index system, the evaluation indices consist of structured numerical data encompassing technical parameter, kinematic and dynamic performance evaluation indices. We label these the headings of the Class I TCCs evaluation index system. Under these headings, we propose evaluation indices, the explanation of these evaluation indices are shown as in Table 1 and Table 2.

In round 1, we present the evaluation indices that have been proposed to be part of the Class I TCCs evaluation index system. We will ask whether you find these evaluation indices relevant for Class I TCCs evaluation index system. For each of these questions, you are given the opportunity to give arguments for your ratings. Finally, we enquire whether you missed any evaluation indices. We will analyse panel members' consensus. Responses will be analysed anonymously. Consensus is defined as content validity ratio (CVR) ≥ 0.62. Evaluation indices not reaching consensus will be presented again in the next round, with your pro and contra arguments, or we will propose an alternative. Your arguments will help us in refining our proposals, taking out items, adding new ones, etc. When we have analysed your argumentation, we will send you an invitation for the second survey round and attach the feedback report of round 1.

In round 2, we will try to reach consensus on the issues left from round 1 based on your ratings and arguments. We will also ask your opinion about potential differentiation, specifically whether certain evaluation indices should be included. If no consensus is reached after two rounds, we will send you an invitation for the third survey round and attach the feedback report from round 2.

In round 3, we aim to reach final consensus on the content of Class I TCCs evaluation index system. We will try to reach consensus on the issues left from round 2 based on your ratings, and we will ask your opinion about potential differentiation, specifically whether certain evaluation indices should be removed. If no consensus is reached after three rounds, the steering committee will make the final decision. The members of the research team will not act as panel members.

Informed Consent Agreement

Study Title: Construction of Class I TCCs evaluation index system for cobots

Please read this consent agreement carefully before you decide to participate in the study.

Consent Form Key Information: Participate in survey study about construction of the Class I TCCs evaluation index system for cobots. Take three surveys over a period of 2 months (time per survey: 60-70 minutes).

Purpose of the research study: The study aims to attain consensus on what indices should be included in the Class I TCCs evaluation index system for cobots.

What you will do in the study: In this study, you will be asked to complete three surveys. In these surveys, you will be presented with proposed evaluation indices that could be useful for Class I TCCs evaluation index system. You will be asked to evaluation indicate to which extent you think a evaluation index is essential. After each question, you can provide arguments for your ratings. We will analyse your ratings and connected arguments, summarize these in a feedback report and send this to you for your review. In total, you will be asked to fill in three surveys and (optionally) review one feedback report.

Data Collected: We will collect your ratings and accompanying statements and calculate consensus for each evaluation index. We define consensus as CVR ≥ 0.62. Provided arguments are discussed with the projects' steering committee to make sense of your suggestions and prepare the next survey round. If there is no consensus, we will investigate subgroup consensus since the disagreement may be caused by differences in disciplinary field or other factors. During this survey, you may skip any question that makes you uncomfortable and/or stop the survey at any time. However, we appreciate your expert opinion and hope you will be able to complete as much as possible.

Time Required: The study will require about 1 hours of your time.

Risks: There are no anticipated risks in this study.

Benefits: There are no direct benefits to you for participating in this research study.

Confidentiality: Your data will only be released anonymously, which means that your name will not be linked to the data. You have received a personalized link, and we will use the email address associated with this link to send a summary feedback report upon our completion of the analysis of the survey, but we will not link your email address to the survey data and the emails will never be released. Your survey data will be recorded, stored, and shared anonymously using an individually assigned identification number.

Voluntary participation: Your participation in the study is completely voluntary.

Right to withdraw from the study: You have the right to withdraw from the study at any time without penalty. How to withdraw from the study: If you would like to withdraw, please contact Jing Zhao (zhaojing@bjut.edu.cn). You do not have to indicate a reason for withdrawal. There is no penalty for withdrawing. Answers that have already been submitted will not be deleted.

Payment: You will receive no payment for participating in the study.

Using data beyond this study: The researcher would like to make the information collected in this study available to other researchers in some case after the study is completed. The researcher will remove any identifying information (such as your name, contact information, etc.) connected to the information you provide. Aggregated and anonymous data will be shared with other researchers for future studies. You will not be asked to give your permission for each new study, as your name and other information that could potentially identify you nor will they attempt to identify you will not be shared.

If you have questions about the study, please contact:

Jing Zhao, Professor

College of Mechanical & Energy Engineering, Beijing University of Technology, Beijing, 100124, China
zhaojing@bjut.edu.cn

Jiwei Yao, PhD Candidate
College of Mechanical & Energy Engineering, Beijing University of Technology, Beijing, 100124, China
JiweiYao@emails.bjut.edu.cn

Zhiang Zhao, Master's Student
Department of Mathematics, University of Maryland, College Park, Maryland, 20742, United States
zzhao98@umd.edu

Agreement: I agree to participate in the research study described above. By selecting 'yes' below, I agree to participate in this survey. I understand the nature of the study and I am participating voluntarily. I understand that I can withdraw at any time, without any penalty or consequences.

☐ Yes

☐ No

Instructions for completing the Delphi

Instructions 1:

You can see our draft proposal for a Class I TCCs evaluation index system form Table 1 and Table 2. This is not the final form, it just serves to give you an overview of the evaluation indices that we will cover. The total questionnaire consists of 33 proposals to review. The evaluation indices are split between two parts: technical parameter evaluation indices (14 proposals) as well as kinematic and dynamic performance evaluation indices (19 proposals). We will ask you to rate your agreement with each proposal on a 5-point Likert scale ('strongly agree' to 'strongly disagree', that is from 5 to 1 point). We aim to identify all relevant evaluation indices of the construction of Class I TCCs evaluation index system for cobots.

The 5-point Likert scale is as following:

Strongly Agree:5, Agree=4, Neutral=3, Disagree=2, Strongly Disagree=1.

Instructions 2:

The survey will request you answer all questions that require a rating. If you feel like you do not have the experience to answer a question, you can select the'no expertise' answer option. In this case, your vote is not considered when calculating the CVR. All the argument boxes are voluntary. However, we highly value your arguments, since we can refine our proposals based on your arguments.

Questionnaire

Technical parameter evaluation indices:

1.1 To what extent do you agree to use the degree of freedom?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.2 To what extent do you agree to use the mass?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.3 To what extent do you agree to use the conventional power consumption?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.4 To what extent do you agree to use the peak power consumption?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.5 To what extent do you agree to use the real load?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.6 To what extent do you agree to use the IP level?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.7 To what extent do you agree to use the maximum speed of each joint?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.8 To what extent do you agree to use the range of each joint motion?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.9 To what extent do you agree to use the maximum torque of each joint?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.10 To what extent do you agree to use the absolute positioning accuracy?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.11 To what extent do you agree to use the repetitive positioning accuracy?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.12 To what extent do you agree to use the arm span of robot?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.13 To what extent do you agree to use the bed area?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

1.14 To what extent do you agree to use the maximum end-effector linear velocity?
Answer: ☐1 ☐2 ☐3 ☐4 ☐5 ☐no expertise

Kinematic and dynamic performance evaluation indices:

2.1 To what extent do you agree to use the x_{11}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.2 To what extent do you agree to use the x_{12}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.3 To what extent do you agree to use the x_{13}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.4 To what extent do you agree to use the x_{14}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.5 To what extent do you agree to use the x_{15}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.6 To what extent do you agree to use the x_{16}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.7 To what extent do you agree to use the x_{21}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.8 To what extent do you agree to use the x_{22}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.9 To what extent do you agree to use the x_{23}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.10 To what extent do you agree to use the x_{24}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.11 To what extent do you agree to use the x_{31}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.12 To what extent do you agree to use the x_{32}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.13 To what extent do you agree to use the x_{33}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.14 To what extent do you agree to use the x_{41}?
Answer: □1 □2 □3 □4 □5 □no expertise

2.15 To what extent do you agree to use the x_{42} ?

Answer: □1 □2 □3 □4 □5 □no expertise

2.16 To what extent do you agree to use the x_{43} ?

Answer: □1 □2 □3 □4 □5 □no expertise

2.17 To what extent do you agree to use the x_{44} ?

Answer: □1 □2 □3 □4 □5 □no expertise

2.18 To what extent do you agree to use the x_{45} ?

Answer: □1 □2 □3 □4 □5 □no expertise

2.19 To what extent do you agree to use the x_{46} ?

Answer: □1 □2 □3 □4 □5 □no expertise