

Evaluation Method for Multi-Operator and Multi-Robot Teleoperation Systems

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Abstract—This paper focuses on the topic of evaluation method for Multi-Operator and Multi-Robot (MOMR) teleoperation systems. First, a new evaluation method for MOMR teleoperation systems was proposed, and the corresponding grouping method of terminals and robots in system and its group evaluation method we proposed was discussed. Second, ten kind of universal capabilities covering 128 functional items and 64 quantitative items were summarized for four operation mode evaluation in the process of group evaluation. Then group evaluation capabilities and items covering 11 functional items and 10 quantitative items were summed up for the comprehensive evaluation of Single-Operator Multi-Robot (SOMR) operation mode group (SOMROMG), Multi-Operator Single-Robot (MOSR) operation mode group (MOSROMG), and Multi-Operator Multi-Robot (MOMR) operation mode group (MOMROMG). Then evaluation capabilities and items covering 19 functional items and 10 quantitative items were also listed for the evaluation of intermediate service node of MOMR operation mode. Finally, through example the effectiveness of the proposed method was validated.

Keywords—evaluation method; Multi-Operator and Multi-Robot (MOMR) teleoperation systems; universal capabilities; grouping method; evaluation items

I. INTRODUCTION

Teleoperation, also known as remote control of robots, is a hot topic in the field of information technology now and a complex multidisciplinary application technology involving robotics, computer science, instruments, dynamics and control, etc [1]. The operating platform based on it can not only complete the information integration tasks such as data processing and image display, providing decision-making help for the operator to participate in the task, also effectively apply various operating modes to the task flow to realize the task safely and quickly [2], [3]. Therefore, teleoperation system of robots is widely applied in deep sea exploration, space exploration and harsh environment operation, etc [3], [4].

In practical applications, a teleoperation task may require multiple operators to cooperatively and remotely control multiple robots to perform cooperation, and operators/robots may be located in different positions, that is a Multi-Operator and Multi-Robot (MOMR) teleoperation systems. In the whole task process, all operator terminals and robots are connected to a communication system, and there is a cooperate teleoperation technology problem between operator and operator, operation decision maker and decision maker. All operators need to

complete cooperatively the teleoperation task under the command of operation decision maker [5]–[7]. The reliability of cooperative operation among operator terminals, the decision-making and interoperability capability among operators, and the decision-making capability of different regions are crucial factors affecting the teleoperation effectiveness, flexibility and task security of robots [8], [9].

However, for the completion of the teleoperation task, the execution result can only be seen after the entire task is completed; and for the task execution capability and interoperability of various terminals, the effect of operational environment in different region on the respond speed of terminal, etc. cannot be evaluated in a timely and effective manner during the execution of the entire task and after the completion of the task. So this paper introduces how to evaluate a MOMR teleoperation systems by its previous task(s) data and establishes a universal evaluation systems for MOMR teleoperation systems. In the paper, Section II treats evaluation method for MOMR teleoperation systems. Evaluation example of a teleoperation systems is analyzed based on the proposed method in Section III. The last Section IV gives the conclusion.

II. EVALUATION METHOD

We firstly give the evaluation method flow chart directly for a MOMR teleoperation systems shown in Fig. 1. From the flow chart we know, specific teleoperation task(s) data of each group after terminals and robots grouping is evaluated and statistical results are used for the further MOMR teleoperation systems evaluation. Then steps of the evaluation method are discussed in detailed. In Section II-B, we introduce the grouping method for operator terminals and robots of a MOMR teleoperation systems based on specific teleoperation task flow. The next Section II-C and II-D discusses the evaluation method of each group and the MOMR teleoperation systems evaluation method.

A. MOMR Teleoperation Systems

MOMR teleoperation systems indicates that $M(M>1)$ operator terminals with different delay environments at the same/different location and homogeneous/heterogeneous $N(N>1)$ operation objects (such as robots, manipulator, etc.)

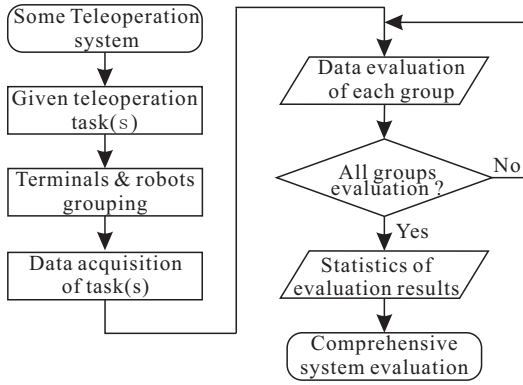


Fig. 1. Evaluation method flow chart for MOMR teleoperation systems

distributed at the same/different site are connected to the same manipulate network, and time synchronization is maintained continually among all terminals, and between terminals and objects; based on the above, N objects are manipulated remotely by M terminals to collaborate to complete a particular teleoperation task.

B. Terminals & Robots Grouping

According to the flow of teleoperation task(s), $M(M>1)$ operator terminals and $N(N>1)$ operation objects (robots) of a MOMR teleoperation systems are grouped before the execution of the teleoperation task(s), each of which includes at least one terminal and one object. The aboved grouping specifically refers to that one/more terminals and one/more object are grouped into a task operation mode group we called according to their mapping relationship of remote control, each of which includes at least one terminal and one object. Where the operator terminal(s) grouped in a task operation mode group is called an operator terminal group, and the operation object(s) is called an operation object group; each operator terminal group has its corresponding operation object group and the total number of task operation mode groups is equal to the total number of operator terminal groups or operation object groups. And according to the number of terminal(s) and object(s) in each task operation mode group, task operation mode group can be divided into four types including Single-Operator Single-Robot (SOSR) operation mode group (SOSROMG), Single-Operator Multi-Robot (SOMR) operation mode group (SOMROMG), Multi-Operator Single-Robot (MOSR) operation mode group (MOSROMG) and Multi-Operator Multi-Robot (MOMR) operation mode group (MOMROMG).

SOSR operation mode is that one operator terminal and one operation object (such as robots, manipulator, etc.) are connected to the same manipulate network, and time synchronization is maintained continually between them to remotely complete a particular teleoperation task. Similarly, operation mode of SOMR with one terminal and n_1 ($n_1 \geq 1$) objects, MOSR with m_1 ($m_1 \geq 1$) terminals and one object, MOMR with m_1 ($m_1 \geq 1$) terminals and n_1 ($n_1 \geq 1$) objects can be known.

When grouping specifically, firstly, according to the flow of the loaded i -th ($k = 1, 2, \dots, R$, R is the total number of effective teleoperation task(s)) teleoperation task and combined with the actual situation of all terminals and objects, terminals and objects of MOMR teleoperation system are divided into groups of v_i ($v_i \geq 1$), that is, all terminals are divided into operator terminal groups of v_i ($v_i \geq 1$), and all objects are divided into operator object groups of v_i ($v_i \geq 1$). Secondly, the v_i groups of operator terminals and operation objects with the corresponding mapping relationship are further divided into SOSROMG of w_i ($w_i \geq 0$), SOMROMG of x_i ($x_i \geq 0$), MOSROMG of y_i ($y_i \geq 0$), MOMROMG of z_i ($z_i \geq 0$), and

$$v_i = w_i + x_i + y_i + z_i$$

Note that when dividing groups, all terminals mapping the same object in the M operator terminals are divided into one operator terminal group, and all objects remotely manipulated by the same terminal in the N operation objects is divided into one operation object group, that is, one terminal may be divided into multiple operator terminal groups, and any object can only be grouped into one operation object group.

C. Evaluation Method of Group

MOMR teleoperation systems is mainly developed for multiple operators to control multiple space robots to fulfill various space tasks. To obtain a better systems evaluation results, it's firstly necessary to develop the method of each task operation mode group.

1) *Data Acquisition of Task(s)*: During the entire process of teleoperation task(s) execution, when remotely manipulating one/more objects in the n_2 operation objects, one/more terminals in the m_2 operator terminals generate the teleoperation request and send it to the intermediate service node, and then generate the corresponding teleoperation instructions and execution time for objects to complete the operation request after receiving the permission from the intermediate service node. Similarly, one/more terminals in the M operator terminals of a MOMR teleoperation systems remotely manipulate one/more objects in the N operation objects only after the permission from the intermediate service node. Based on the above, complete task(s) data of each task operation mode group can be acquired. A large number of teleoperation tasks should be executed for the achievement of better evaluation of each group.

2) *Evaluation Method of Group*: Based on the combination of the acquired groups data and all quantitative and functional evaluation items shown in the following section, the group evaluation result indicated by E_i of i -th ($k = 1, 2, \dots, R$) is given by Eq. (1). Where assume that the j -th universal capability has m functional evaluation items and n quantitative evaluation items.

$$E_i = \sum_{j=1}^S (\alpha_j^T \mathbf{P}_j + \beta_j^T \mathbf{Q}_j) \quad (1)$$

Where α_j and β_j are weight matrix of functional and quantitative evaluation items respectively, and the value of their

element α_{jk} ($k = 1, 2, \dots, f$) and β_{jl} ($l = 1, 2, \dots, g$) is determined by the relative importance among all evaluation items.

$$\alpha_j = [\alpha_{j1}, \alpha_{j2}, \dots, \alpha_{jf}]^T;$$

$$\beta_j = [\beta_{j1}, \beta_{j2}, \dots, \beta_{jg}]^T,$$

and

$$0 \leq \alpha_{jk}, \beta_{jl} \leq 1;$$

$$\sum_{k=1}^f \alpha_{jk} + \sum_{l=1}^g \beta_{jl} = 1.$$

\mathbf{P}_j and \mathbf{Q}_j are evaluation value of functional and quantitative evaluation items respectively, and the value of their element p_{jk} ($k = 1, 2, \dots, f$) and q_{jl} ($l = 1, 2, \dots, g$) is equal to 0 or 1, determined by whether the criteria is satisfied.

$$\mathbf{P}_j = [p_{j1}, p_{j2}, \dots, p_{jf}]^T;$$

$$\mathbf{Q}_j = [q_{j1}, q_{j2}, \dots, q_{jg}]^T,$$

and

$$p_{jk} = \begin{cases} 1, & \text{if } k\text{-th item is satisfied} \\ 0, & \text{otherwise.} \end{cases}$$

$$q_{jl} = \begin{cases} 1, & \text{if } l\text{-th item is in target range} \\ 0, & \text{otherwise.} \end{cases}$$

Evaluation of SOSR operation mode is completed mainly from 8 universal capabilities shown in Fig. 2, and each capability has its corresponding m functional evaluation items and n quantitative evaluation items shown in Fig. 3. Where items marked with "*" are the quantitative evaluation items whose quantized value directly reflects the evaluation results of the corresponding evaluation item, and unmarked items are the functional evaluation items whose evaluation results are reflected by whether to has the function of the corresponding item. SOSROMG is evaluated according to Eq. (1), and iteration evaluation result is indicated by E_i^1 .

Similarly, SOMR, MOSR, and MOMR operation mode can also be evaluated according to Eq. (1), and some universal capabilities or evaluation items for the evaluation of SOMROMG, MOSROMG, and MOMROMG are added on the basis of that of SOSROMG, shown in Fig. 2.; Besides, group evaluation capabilities and items are given for the comprehensive evaluation of SOMROMG, MOSROMG, and MOMROMG, and evaluation capabilities and items for intermediate service node of MOMR operation mode are also added, shown in Fig. 4. Their result are indicated by E_i^2 , E_i^3 , and E_i^4 respectively.

D. Evaluation Method for MOMR Teleoperation Systems

1) *Statistics of Evaluation Results:* Before we give the comprehensive MOMR teleoperation evaluation, we first must complete evaluation of all R tasks data acquired in Section II-C1 based on evaluation method given in Section II-C2. Then Statistics of the above evaluation results of all groups can be further obtained.

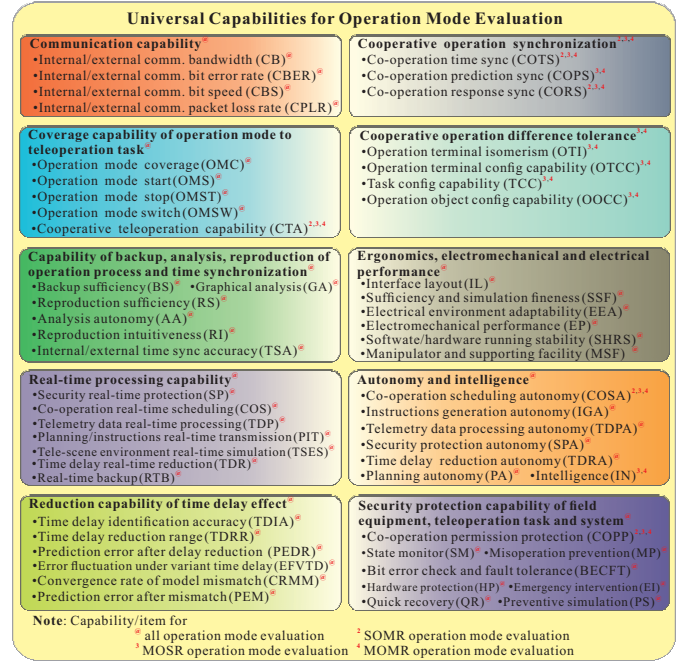


Fig. 2. Universal capabilities for operation mode evaluation

2) *Comprehensive Systems Evaluation:* The comprehensive MOMR teleoperation systems evaluation can be defined as follows according the statistics results of R tasks data, and its evaluation result is indicated by E_R .

$$E_R = \sum_{i=1}^R c_i \mathbf{G}_i \mathbf{E}_i \quad (2)$$

Where c_i ($0 \leq c_i \leq 1$) is the complexity coefficient of i -th teleoperation task and is used to reflect the complexity of a teleoperation task. \mathbf{G}_i and \mathbf{E}_i are the grouping coefficient matrix and evaluation result matrix of groups of the i -th teleoperation task respectively, and

$$\mathbf{G}_i = \begin{bmatrix} w_i & x_i & y_i & z_i \\ v_i & v_i & v_i & v_i \end{bmatrix};$$

$$\mathbf{E}_i = [E_i^1, E_i^2, E_i^3, E_i^4]^T.$$

III. EXAMPLE

In order to validate the aboved method, the comprehensive evaluation of a Multi-Operator and Single-Robot (MOSR) teleoperation systems shown in Fig. 5 is carried out. The systems is consist of six units including data control and management unit, behaviors simulation unit of objective response, terminal 1, terminal 2, terminal 3 and image processing unit. Based on its teleoperation tasks data acquired, the systems evaluation is completed according to universal capabilities for MOSR operation mode and capabilities and items for MOSROMG shown in Fig. 2 - 4. Given space limitations, this paper only presents two of universal capabilities for systems evaluation as follows, including communication capability, and coverage capability of operation mode to teleoperation task.

Communication capability ^①			Autonomy and intelligence ^②		
CB ^②	*CB among internal units of terminal ^② *CB of terminal and object ^② *CB among terminals ^{3,4}		COSA ^{2,3,4}	Co-operation space assignment autonomy ^{2,3,4} Co-operation order assignment autonomy ^{2,3,4} Co-operation environment perception autonomy ^{2,3,4}	
CBER ^②	*CBER among internal units of terminal ^② *CBER of terminal and object ^② *CBER among terminals ^{3,4}		IGA ^②	Operation interface autonomous change with operation mode ^② Security autonomous judgement of path planning ^② Sequence autonomous generation of path planning ^②	
CBS ^②	*CBS among internal units of terminal ^② *CBS of terminal and object ^② *CBS among terminals ^{3,4}		TDPA ^②	Autonomous coding, verification and sending of instruction sequence ^② Operation instructions backup autonomy ^②	
CPLR ^②	*CPLR among internal units of terminal ^② *CPLR of terminal and object ^② *CPLR among terminals ^{3,4}		SPA ^②	Autonomy of reception, decoding, verification and format conversion ^② Autonomy of telemetry data, image mosaic and refresh ^② Telemetry data backup autonomy ^②	
Coverage capability of operation mode to teleoperation task ^②			Ergonomics, electromechanical and electrical performance ^②		
CTA ^{2,3,4}	SOMR operation mode ^{2,3,4} MOSR operation mode ^{3,4} MOMR operation mode ^④	Simultaneous operation mode ^{2,3,4} Time sharing operation mode ^{2,3,4}	TDRA ^②	Autonomy of state monitor, data statistics and refresh ^② Error Correction, misoperation prevention and abnormality alert ^② Backup autonomy of abnormality and data statistics ^②	
OMC ^②	Autonomous/monitoring mode ^② Macro mode ^② Preprogramming mode ^② Interactive mode ^②	Numerical interaction mode ^② Operator interaction mode ^{2,3,4}	PA ^②	Time delay identification autonomy ^② Mismatch correction autonomy ^② Delay reduction and prediction autonomy ^② Tele-scene simulation autonomy ^② Backup autonomy of delay reduction process record ^②	
OMS ^②	Start at any mode ^②	*Elapsed time ^②	IN ^{3,4}	Division capability of others into assist/observation terminal by main terminal ^{1,4} Co-processing capability of manipulate request from terminal by main terminal ^{1,4} *Co-processing toplimit of manipulate request from terminal by main terminal ^{1,4} *Toplimit of terminals participating in manipulation ^{1,4} Online adaptive capability of terminal ^{1,4} State display capability of corresponding object by terminal ^{1,4}	
OMST ^②	Stop at ny mode ^②		Ergonomics, electromechanical and electrical performance ^②		
OMSW ^②	Switch at any mode ^②				
Capability of backup, analysis, reproduction of operation process and time synchronization ^②					
BS ^②	Telemetry data backup ^② Instructions backup ^② Abnormal results backup ^②	Co-operation data backup ^{2,3,4} Co-operation Permission change backup ^{2,3,4} Co-operation abnormality backup ^{2,3,4} Co-operation scheduling backup ^{2,3,4}	IL ^②	Clear and eye catching ^② Reasonable layout and easy to check ^②	
GA ^②	Interaction data backup ^②	Co-operation delay environment backup ^{2,3,4} Co-operation interaction data backup ^{2,3,4} Co-operation statistical data backup ^{2,3,4} Co-operation running process backup ^{2,3,4}	SSF ^②	Feedback information sufficiency ^② Prediction data and operation record sufficiency ^② Simulated environment intuitiveness ^②	
AA ^②	Statistical data backup ^②		EEA ^②	Equipped with DPU and UPS ^② *Tolerated fluctuation range of voltage ^② *Sustainable work time after power-off ^②	
RI ^②	Delay reduction data backup ^②		EP ^②	*Adaptation range of temperature, humidity and pressure ^② *Size and weight ^②	
RS ^②	Running process backup ^②		SHRS ^②	*Software stable running duration ^② *Hardware stable running duration ^②	
TSA ^②	*TSA among internal units of terminal ^② *TSA of terminal and object ^②	Co-operation running process backup ^{2,3,4} *CB among terminals ^{3,4}	MSF ^②	Hardware completeness ^② Software completeness ^② Audio interactive equipment ^② Video screen monitor equipment ^② External video output device ^② Data analysis software ^② Playback software ^② Synchronization software ^②	
Real-time processing capability ^②					
SP ^②	*Monitoring state refresh frequency ^②				
COS ^②	*Cognitive time of environment change ^② *Elapsed time of requested operation receipt ^② *Refresh time of operation space assignment ^②				
TDP ^②	*Telemetry data refresh frequency ^② *Telemetry image refresh frequency ^②				
PIT ^②	*Mean interval sending instructions in planning ^② *Mean interval sending instructions from operator ^②				
TSES ^②	*Simulation refresh frequency ^② *Mean Simulation refresh frequency of terminals ^{3,4}				
TDR ^②	*Mean time between tele-data arrival time and prediction time ^②				
RTB ^②	*Ratio of backup data size and actual data size ^②				
Reduction capability of time delay effect ^②			Cooperative operation difference tolerance ^{3,4}		
TDIA ^②	*Time delay identification accuracy of co-interaction		OTI ^{3,4}	Interaction interface isomerism ^{3,4} Operator ^{3,4}	
TDRR ^②	*Time delay identification accuracy of teleoperation		OTCC ^{3,4}	Terminal architecture isomerism ^{3,4} Tele-terminal unit ^{3,4}	
PEDR ^②	*Time delay reduction range of co-interaction		TCC ^{3,4}	Delay reduction strategy ^{3,4}	
EFVTD ^②	*Time delay reduction range of teleoperation		OCC ^{3,4}	Tele-terminal function ^{3,4}	
CRMM ^②	*Variant delay error fluctuation of co-interaction		OCC ^{3,4}	Tele-terminal running process ^{3,4}	
PEM ^②	*Variant delay error fluctuation of teleoperation				
Cooperative operation synchronization ^{2,3,4}					
COTS ^{2,3,4}	Co-operation terminal time sync ^{3,4} Co-operation object time sync ^{2,3,4} Intermediate service node time sync ^④		*Marked time difference of terminal for the same event ^{3,4} *Marked time difference of object for the same event ^{2,3,4} *Marked time difference of node for the same event ^④		
COPS ^{3,4}	MOSR operation prediction sync ^{3,4} MOMR operation prediction sync ^④		*Response prediction start-end marked time difference of terminal for the same operation ^{3,4} *Response prediction start-end marked time difference of terminal for the same operation ^④		
CORS ^{2,3,4}	MOSR operation response sync ^{3,4} MOMR operation response sync ^④		*Response start time difference of object for the same operation ^{3,4} *Response marked time difference of object for simultaneous operation of terminals ^④		
Security protection capability of field equipment, teleoperation task and system ^②					
COPT ^{2,3,4}	Sharing permission of MOSR ^{3,4} Sharing permission of MOMR ^④	Simultaneous operation weight assignment ^{2,3,4} Simultaneous operation permission change ^{2,3,4}	Time sharing operation alternate permission ^{2,3,4} Time sharing operation permission protection ^{2,3,4}		
SM ^②	Coverage Range ^② Operation tips ^② *Miss rate ^②	Link state of operator ^② Link state of links ^② Data interaction statistics and bit speed ^② Operation tips and operation record tips ^② *Abnormal miss rate of telemetry data ^② *Abnormal miss rate of system state ^②	Telemetry data loss, bit error and statistics ^② Instructions over bound, over speed and bit error ^② Abnormal situation alert ^② *Abnormal miss rate of instructions ^②		
BECFT ^②	*Wrong instruction sending rate ^②		Tolerance abnormality rate of telemetry data ^②		
HP ^②	Acceleration and deceleration capability ^② Preview simulation function ^②		*Peak error of simulation and reality ^② *Mean error of simulation and reality ^②		
MP ^②	Software misoperation prevention ^② Hardware misoperation prevention ^②	Operation mode lock function ^② Operator software enabling and smooth output ^② Operator hardware enabling and smooth output ^②	Instructions error alert and prevention ^② Operator anti shake ^②		
EI ^②	Emergency stop function ^② Emergency operation function ^②		*Emergency intervention mode switch time ^②		
QR ^②	Hardware interruption recovery ^② Software interruption recovery ^②		*Hardware recovery time ^② *Software recovery time ^②		
PS ^②	Power supply protection ^② Communication protection ^② Other protection ^②	*Tolerated fluctuation range of voltage ^② *Sustainable work time after power-off ^② Have alternate channel ^② Anti dust function ^② Antistatic function ^② Anti-electromagnetic interference function ^②	Power-off protection function ^② *Switch time of alternate channel ^② Anti seismic function ^②		

Note: ^①quantitative evaluation item; Capability/item for ^②all operation mode evaluation ^③SOMR operation mode evaluation ^④MOMR operation mode evaluation.

Fig. 3. Functional/quantitative evaluation items for universal capabilities

Group Evaluation Capability & Item ^{2,3,4}		
Capability	Evaluation Content	Evaluation Item
Extensibility of Group ^{2,3,4}	Extensibility for terminal ^{3,4}	Allow new terminal to participate in manipulation when in operation ^{3,4} *Toplimit of allowed terminal ^{3,4} Allow new terminal to participate in manipulation when in non operation ^{3,4} *Toplimit of allowed terminal ^{3,4}
	Extensibility for object ^{2,4}	Allow new object to participate in manipulation when in operation ^{2,4} *Toplimit of allowed object ^{2,4} Allow new object to participate in manipulation when in non operation ^{2,4} *Toplimit of allowed object ^{2,4}
	Extensibility for software ^{2,3,4}	Extensibility for software module of other functions ^{2,3,4}
Difference Tolerance of Group ^{2,3,4}	Tolerance for terminal ^{3,4}	Tolerance for multiple heterogeneous terminals ^{3,4} *Toplimit of heterogeneous terminal ^{3,4} Allow any terminal to main terminal ^{3,4} *Toplimit of assist/obsetvation terminal ^{3,4}
	Tolerance for object ^{2,4}	Tolerance for multiple different function/config objects ^{2,4} *Toplimit of different function/config objects ^{2,4}
	Tolerance for delay ^{2,3,4}	Tolerance for multiple terminals with different delay ^{2,4} *Tolerable delay range of terminal ^{3,4} Tolerance for multiple objects with different delay ^{2,4} *Tolerable delay range between terminal and object ^{2,4}
	Tolerance for task ^{2,3,4}	Tolerance for tasks with different complexity ^{2,4} *Tolerable complexity range of task ^{2,4}
Evaluation Capability & Item for Intermediate Service Node of MOMR Operation Mode		
Capability	Evaluation Content	Evaluation Item
Autonomy and intelligence	Multi objets/tasks support capability	Grouping capability for terminals & objects *Toplimit of terminals when grouping *Toplimit of objects wshen grouping
	Autonomy of state judgment, reception and sending	Judgment autonomy of operating state of terminal/object Reception autonomy of operating state from terminal/object Sending autonomy of operating state of all terminals/objects to authorized terminal
	Response and sending autonomy of manipulate request	Storage/replacement autonomy of operating state from terminal/object Sending autonomy of state infor. to all terminals
	Autonomy of transmission delay monitoring and maintenance	Autonomy of request response from terminal Sending autonomy of request permission to terminal
Real-time processing capability	Real-time of state judgment, reception and sending	*State judgment refresh frequency of terminal/object *Mean time difference between state sending and receiving *Mean elapsed time of state reception from terminal/object *Storage/replacement refresh frequency of state *Mean elapsed time of state sent to all terminals/objects
	Real-time response and sending of manipulate request	*Mean elapsed time of request response from terminal *Mean elapsed time of sending request permission to terminal
	Real-time maintenance of transmission delay	*Maintenance refresh frequency of delay stored in intermediate service node
Synchronization capability	Time sync capability	Time sync of intermediate service node *Time difference of sending-reception time difference and measured delay
	Response sync capability	Response sync of intermediate service node *Response time difference of one terminals at the same time *Response time difference of different terminals at the same time

Note: *quantitative evaluation item; Capability/item for ² SOMROMG evaluation ³ MOSROMG evaluation ⁴ MOMROMG evaluation.

Fig. 4. Capabilities and items for SOMROMG, MOSROMG, and MOMROMG evaluation, and functional/quantitative evaluation items for intermediate service node of MOMR operation mode

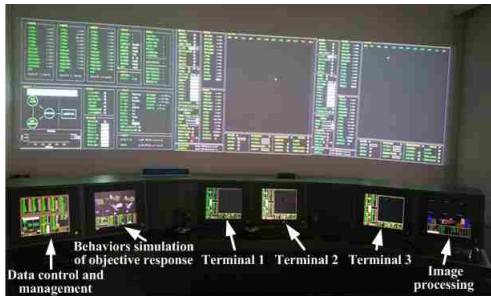


Fig. 5. Some MOSR teleoperation systems

A. Communication capability

1) Internal/external communication bandwidth (CB):

- *CB among internal units of terminal: 1000 Mbps
- *CB of terminal and object: master channel: 54 Mbps (wireless), slave channel: 100 Mbps (wired)

2) Internal/external communication bit error rate (CBER):

- *CBER among internal units of terminal: $\leq 0.01\%$
- *CBER of terminal and object: $\leq 0.02\%$

3) Internal/external communication bit speed (CBS):

- *CBS among internal units of terminal: 27.5 Mbps
- *CBS of terminal and object: 9.3 Mbps

4) Internal/external communication packet loss rate (CPLR):

- CBS among internal units of terminal: $\leq 0.03\%$
- CBS of terminal and object: $\leq 0.05\%$

B. Coverage capability of operation mode to teleoperation task

1) Cooperative teleoperation capability (CTA):

- SOMR operation mode:
- MOSR operation mode:
- MOMR operation mode:
- Simultaneous operation mode:
- Time sharing operation mode:

2) Operation mode coverage (OMC):

- Autonomous mode(AM):
- Monitoring mode (MAM):
- Macro mode (MM):
- Preprogramming mode (PPM):
- Numerical interaction mode (NIM):
- Operator interaction mode (OIM):

3) Operation mode start (OMS), Operation mode terminal (OMT) and Operation mode switch (OMSW):

- Start at any mode start:
- Stop at any mode:
- Switch at any mode :
- *Elapsed time: shown in Table I.

TABLE I
ELAPSED TIME OF OPERATION MODE START, STOP, AND SWITCH

	AM/MM	MAM	PPM	NIM/OIM
Start	4.5s	6.5s	6.5s	7.0s/9.0s
Stop	3.0s	3.0s	3.0s	3.0s
Switch to AM/MM	/	4.5s	4.5s	5.5s
MAM	5.5s	/	3.5s	5.5s
PPM	5.5s	3.5s	/	5.5s
NIM/OIM	7.0s/9.0s	7.0s/9.0s	7.0s/9.0s	4.0s/4.0s

C. Systems evaluation

From the evaluation method described in Section II, the weight matrix and corresponding evaluation value of the first and second universal capability can be obtained as follows.

$$\mathbf{P}_1 = \mathbf{0}; \mathbf{Q}_1 = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}_{12 \times 1}$$

$$\mathbf{P}_2 = [1, 1, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1]^T; \mathbf{Q}_2 = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}_{26 \times 1}$$

Then we can give the corresponding weight matrix of functional and quantitative evaluation items respectively by systems performance requirements. Similarly, the evaluation value and corresponding weight matrix of the rest universal capabilities in Fig. 3, and group evaluation value in Fig. 4 and corresponding weight matrix for this MOSR teleoperation systems can also be given. After obtaining all evaluation value, the comprehensive systems evaluation can be completed with Eqs. (1) and (2).

IV. CONCLUSION

On the basis of at least one teleoperation task data, a complete comprehensive evaluation method for MOMR teleoperation systems were given in this paper; besides, the grouping method and corresponding evaluation method of each group are discussed in details. 158 functional evaluation items and 84 quantitative evaluation items covering all capabilities were further summarized for operatio mode group and comprehensive evaluation of MOMR system. This method can be applied to qualitatively understand the functionality completeness and analyze the application effectiveness of a MOMR teleoperation systems, which has a guiding role in the overall design and development of cooperative teleoperation for complex system and multi-object.

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