Modeling and Simulation of Automated Container Terminal Operation

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***Abstract*- The growths of containerization and transporting goods in containers have created many problems for ports, especially with the development of operation equipments produced by port machine manufacturer. A simulation study was proposed to a new container terminal handling technology, which is comprised of twin 40-foot quay cranes, a low bridge allocation system and twin 40-foot rail mounted gantry crane (RMG). The loading and unloading process was analysised and container terminal operation conditions are defined under this operation conditions. Based on event-driven and virtual reality technology, the handling technology simulation model was established. The operating efficiency of key equipments is calculated during the simulation. Finally, validation is presented through a case study. The method enriched the contents of container terminal handling technology simulation and laid the foundation for further study of automated container terminal.**

***Index Terms*- automated container terminal (ACT); operation condition; simulation; handling technology; virtual reality**

I. INTRODUCTION

Containerization has revolutionized cargo shipping. Today, approximately 90% of non-bulk cargo worldwide moves by containers stacked on transport ships, which leading to greater volume flows at the container terminals (CT) [1,2,3]. In response to the great amount of containers, larger container ships with capacities of 15,000 twenty-foot equivalent unit (TEU) and beyond are being ordered and going to enter service. On the other hand, new kind of operating infrastructures are designed and manufactured by CT hardware manufacturers with advancements in technology. In the point of view of port operators, they are constantly under pressure to increase the port throughput and reliability, and to keep the container transportation costs at a minimum.

Over the last decade, the study of ACT has gained increasing attention from researchers to raise handling productivity. The CT Altenwerder in the Port of Hamburg, Germany and the Europe CT in Rotterdam, the Netherlands, which are impressive because of their performance, is merely a rare species. However, automation is taken more seriously and developing never stops [4,5,6]. Generally speaking, each CT no matter automated or not consists of three parts: the quayside, where containers are unloaded from and loaded onto ships through quay cranes (QC); the container storage yard, where containers are stored by yard cranes (YC); and the area between the container yard and the quayside, where containers are transported by yard trailers (YT) or AGV within the terminal. Upon a ship's arrival, QC unloads containers from or load containers onto the ship, and YT/AGV move containers from quayside to storage yard and vice versa. At the storage yard, YC perform the loading and unloading for YT/AGV [7]. Recently, to extend the crane loading and unloading unit and explore the application of twin-40-foot quay cranes have become a hot topic in the port industry. In many of the terminal design projects, hardware configuration and new container terminal layout are designed and new-style automated handling system is adopted after preoperation [8]. Conventional QC has a lift capacity of one container. New developments are cranes with twin or tandem lift ability. Four adjacent 20-foot containers or two 40-foot containers, respectively, can be lifted at once. The cranes are equipped with a specific twin container spreader. Mechanical linkages between the two spreaders facilitate the adjustment to different container heights as well as to side-to-side clearances of two containers quayside while landing them onto adjacent yard chassis. Twin lift cranes are designed for faster loading/unloading operations in order to meet the demands of mega-vessels. The twin handling can be supported by AGVs operating side by side. The container terminal is expected to boost the productivity by up to 50% if loading/unloading techniques are improved accordingly [9,10,11].

In this paper, we introduce, analyze a kind of ACT, which based on the configuration of twin-40-foot quay cranes in quayside, a low bridge allocation system for transportation and twin-40-foot RMG in the storage yard. This paper provides an illustration of the ACT and the new problem result from this innovation. The main emphasis is placed on its handling technology modeling and simulation under multiple operation conditions. A

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doi:10.4304/jcp.5.6.951-957

major goal of this paper is to evaluate the utilization of the developed ACT system and make this method as a decision making tool for port administration department.

This paper is organized as follows: the next section gives detailed illustration of the proposed ACT and provides the problem formulation. In section 3 a model is developed that is used to simulate all the operations of the ACT, followed by the simulation scenarios and computational experiments in section 4. Furthermore, the performance evaluation and simulation method used in this paper are discussed. In the final section, the paper is concluded with a summary and outlook identifying interesting and promising topics for future research.

II. PROBLEM DESCRIPTION

A. ZACT handling technologies

Usually, there are two kinds of containers served at any CT. Inbound containers are brought in the port by vessels for import into land, whereas outbound containers are brought in by transport equipments and for loading onto vessels in order to export. According to the flow of containers inside the CT, the Container Terminal Handling Technology (CTHT) can be divided into three parts. Namely, loading to/unloading from the container ship, container transport between the vessel and yard and storage yard operation. The quayside consists of a limited number of berths, each of which is equipped by QC that plays an important role in the CT. When the container vessel arrived at the berth, the cranes are used to load containers to vessels and unload containers from vessels. Then, containers are transported between the QCs and storage yard by internal trucks or AGVs. The storage yard serves as temporary buffers for inbound and outbound containers. The YC is in charge of loading containers to the specified location in the storage yard or moving the containers to the transportation equipment. In each stage of container operation process, different choice of port machine plays key role in its position, this is precisely that the diversity of CT operation equipment forms a variety of combinations of handling technology.

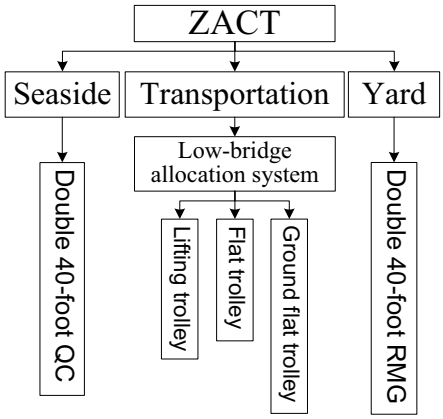

Figure 1. ZACT handling technology structure

In this paper, we are mainly focus on a new type of ACT, which is designed and invented mainly by Shanghai Zhenhua Port Machinery Company (ZACT). It is a demonstration filed of the world's latest ACT and located in Changxing island, Shanghai. As shown in Fig.1, at the seaside, twin 40-foot QC is applied for the loading/unloading; in the storage yard, twin 40-foot RMG is adopted correspondingly; between the quayside and yard, a low bridge allocation system, which is comprised of three kinds of trolleys, is adopted. Besides, different from the current container ports, Fig. 2 shows its layout. In order to describe the operation flow of this new type CT, taking container ship unloading operation as an example. When the ship arrived at the berth, twin 40-foot QC lifting the containers from the vessel and unloading to the flat trolley (FT), then it moves to the unloading position where the ground flat trolley (GFT) can pick by lifting trolley (LT), after that container(s) is transferred to the specified position in the yard by double 40-foot RMG.

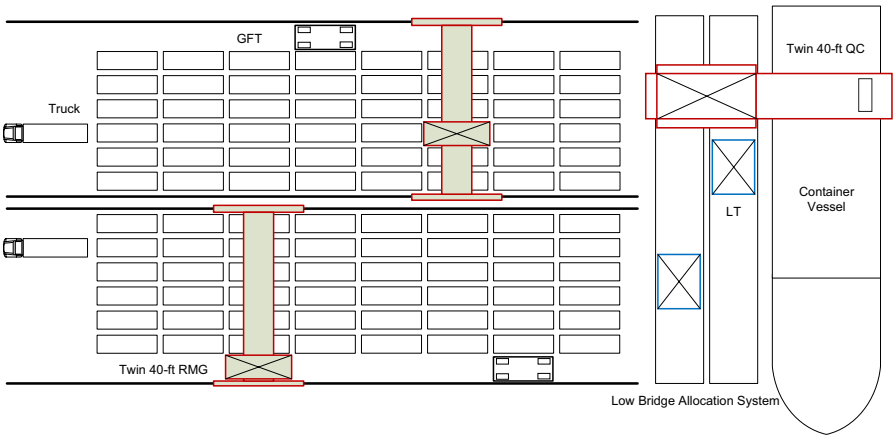

Figure 2. Layout of ZACT

Compared with traditional CT handling process, this ZACT has the following special characters:

(1) Twin 40-foot QC can largely improve the working efficiency. It has two sets of lifting mechanism and can lift two 40-foot or four 20-foot containers at once. Through theoretical calculation, the twin 40-foot QC can improve

the loading and unloading efficiency more than 50% of the traditional one.

(2) The low-bridge allocation system greatly facilitates the container operation. With this innovative allocation system, it is able to transfer any containers from any bay plan to the corresponding berth of any position in the yard; it enables the automatic transfer of the container from one stacking area to another; each quayside crane has one or more effective sidings for loading/unloading, without any interference of the sidings.

(3) The ACT is fully electric powered and without diesel engine, not only improving the degree of automation, but also saving energy and protecting the environment.

B. *Multiple operation conditions of ZACT*

The generation of twin 40-foot QC brings a revolution to the industry of container terminal. With the two sets of independent lifting mechanism, which equipped a separate expandable spreader, twin 40-foot QC has a variety of operating conditions.

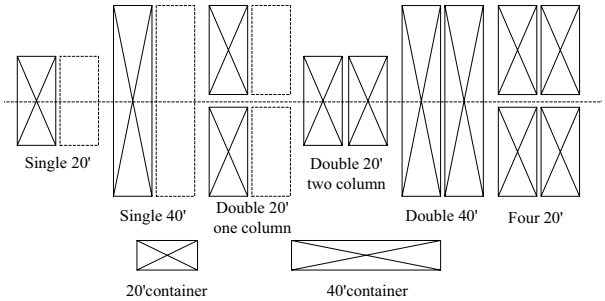

Figure 3. Operation conditions of twin 40-ft QC

Taking into account of the actual operations in the CT, a 20-foot container and 40-foot containers at a time will not happen. Therefore, according to the container combination situation, as shown in Fig. 3, six kinds of operation condition are listed when the QC working. In the Single 20' operation condition, the QC lift only one 20-foot container at once, so the left spreader shrink to fit the 20-foot container's size in advance. The single 40' operation condition is quite the same as Single 20' operation condition, but without spreader shrink. When picking two 20-foot containers, there are two operation conditions according to the position of the containers. One is Double 20' one column when the two containers are located in the same column; the other is Double 20' two column when two containers are in two adjacent columns. However, the later operation condition need both spreaders shrink. The Double 40' and four 20' operation conditions are the highest efficiency operation conditions. In the Double 40' operation condition, the twin 40-foot QC can load two 40-foot containers at once. While in the Four 20' operation condition, the twin 40-foot QC is able to hoist four 20-foot containers at once. This is greatly different from the traditional QC. When the twin 40-foot QC is adopted the operation in the seaside will be much more effective. However, the CT is a systematic project and part efficiency improved does not mean the overall operating efficiency will be increased. In addition, how to fit the challenge caused by new equipment to make the best use of them is worthy of study.

C. *Rules for multiple operation conditions simulation*

As mentioned above twin 40-foot QC has the ability to work under the six common operation conditions. However, different options have an important influence on its efficiency. In other words, with different locations of containers in the yard or vessel, QC should determine which pickup patterns adopted based on some rules. To simplify the description, Fig. 4 shows fifteen 40-foot export containers are in the yard bay with four tiers and six stacks. Twin 40-ft YC and AGV (GFT) are applied. The number marked in the container represents different containers. In this paper, the decision rule for twin 40-ft YC is that containers are located in adjacently stack and each of them is located on top of the stack. According to this rule, as shown in Fig. 4, container A and B can be loaded at a time. While, containers in the same stack like A and D is neglected for extra trolley moves in this study. Meanwhile, YC also needs transfer between stack 2 and 4 when pick up container B and C although they on top of each stack.

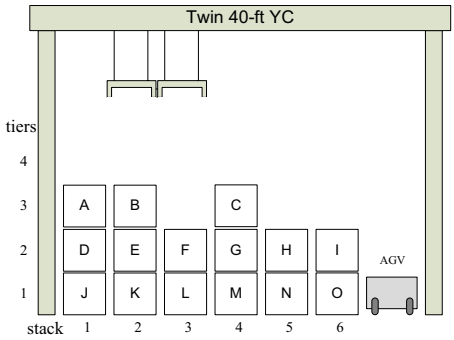

Figure 4. Rules for multiple operation conditions operation

III. MODELING

The three parts of CT loading/unloading operations of cooperate with each other, with the same objective of finishing the operation jobs. Modeling is the basis of simulation, in order to achieve the handling technology simulation of loading and unloading requires not only the establishment model of key equipments (QC, YC and low bridge allocation system). Moreover, the environment model that reflects the realistic situation, but also the kinematics modeling involved in the relative motion of the components.

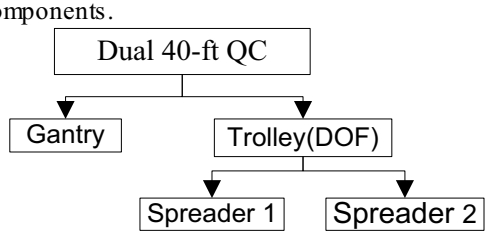

Figure 5. Hierarchical structure tree of dual (twin) 40-ft QC

Considering the particularity of the twin 40-foot QC, the modeling are mainly focus on the spreader lifting, descend and to lengthen and shorten, the start-up and braking of the spreader and crane, as well as the corresponding operation of low bridge and YC. Based on event driving mechanism to make a detailed analysis of the process and build the simulation model. In order to describe the modeling process, take twin 40-foot QC as an example. The hierarchical structure tree of twin 40-foot QC is shown in Fig. 5, take the relative motion object as a DOF (Degrees of Freedom) node, it can control all its child nodes below and have an independent coordinate system that can be compared with the parent node for the relevant motion. The activity diagram of twin 40-foot QC is given in Fig. 6. It shows the workflow of new type QC. According to different container location, the QC chooses appropriate operation conditions.

According to the properties and function of the equipment, the event in the process of container terminal operation is defined. TABLE I shows loading/unloading events of QC in ZACT.

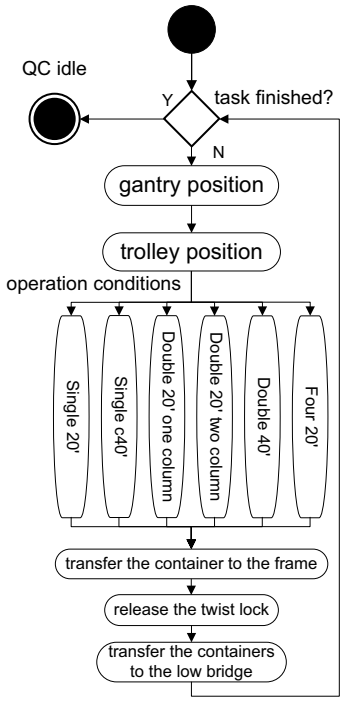

Figure 6. Activity diagram of twin 40-ft QC

TABLE I.
EVENTS OF QC IN ZACT

NO.	Event	Description
1	QC_Crane_Start	Gantry position
2	QC_Spreader_FetchDown	Spreader start to pick the container
3	QC_Spreader_Contract	Spreader start to shrink
4	QC_Spreader_FetchUp	Spreader start to ascend
5	QC_Trolley_Start	Trolley position
6	QC_Spreader_PauseDown	Spreader start to release the twist lock
6	QC_Spreader_PauseUp	Spreader start to ascend after release twist lock
7	QC_Trolley_Release	Trolley start-up
8	QC_Spreader_ReleaseDown	Spreader start to release container
9	QC_Spreader_ReleaseUp	Spreader start to ascend after release container
10	QC_Trolley_Return	Trolley return back

IV. SIMULATION AND ANALYSIS

A. Assumptions

Before a simulation runs, assumptions and limitations of the model have to be identified. Some of the assumptions and limitations considered in developing the port simulation model are as follows:

(1). The container information is known before the loading/unloading operation;

(2). The containership stowage plan and storage yard-stacking plan are given in advance. That means the loading/unloading sequence is known;

(3). The operation condition can be chosen according to the container stacking state;

B. Model input data

Model input data must be easy, simple, rapid, and understandable for the user. In this simulation model, the data have been organized and as shown in TABLE II. These are container information, including container code, size information (20 or 40 foot), initial position (in the ship or yard and its location) and its destination (yard or ship and its coordinate). In TABLE II, there are 24 containers to unload from the ship to two pre-defined yards. The coordinate of source and destination means bay, row and tier number separately.

TABLE II.
CONTAINER INPUT DATA FOR SIMULATION

No.	Container code	Size	Source	X	Y	Z	Destination	X	Y	Z
1	jzx0000045	40	Ship	2	1	3	1	6	2	1
2	jzx0000050	40	Ship	3	1	3	2	10	1	1
3	jzx0000020	40	Ship	1	1	2	1	6	3	1
4	jzx0000025	40	Ship	2	1	2	1	6	4	1
5	jzx0000030	40	Ship	3	1	2	2	10	3	1
6	jzx0000035	40	Ship	4	1	2	2	10	4	1
7	jzx0000000	40	Ship	1	1	1	1	6	5	1
8	jzx0000005	40	Ship	2	1	1	1	6	6	1
9	jzx0000010	40	Ship	3	1	1	2	10	5	1
10	jzx0000015	40	Ship	4	1	1	2	10	6	1
11	jzx0000055	20	Ship	2	3	3	1	12	2	1
12	jzx0000060	20	Ship	3	4	3	2	6	1	1
13	jzx0000065	20	Ship	1	3	2	1	12	3	1
14	jzx0000070	20	Ship	2	3	2	1	12	4	1
15	jzx0000075	20	Ship	3	3	2	2	6	3	1
16	jzx0000080	20	Ship	3	4	2	2	7	3	1
17	jzx0000085	20	Ship	1	3	1	1	12	5	1
18	jzx0000090	20	Ship	2	3	1	1	12	6	1
19	jzx0000095	20	Ship	1	4	1	1	13	5	1
20	jzx0000100	20	Ship	2	4	1	1	13	6	1
21	jzx0000105	20	Ship	3	3	1	2	6	5	1
22	jzx0000110	20	Ship	4	3	1	2	6	6	1
23	jzx0000115	20	Ship	3	4	1	2	7	5	1
24	jzx0000120	20	Ship	4	4	1	2	7	6	1

C. Simulation experiments

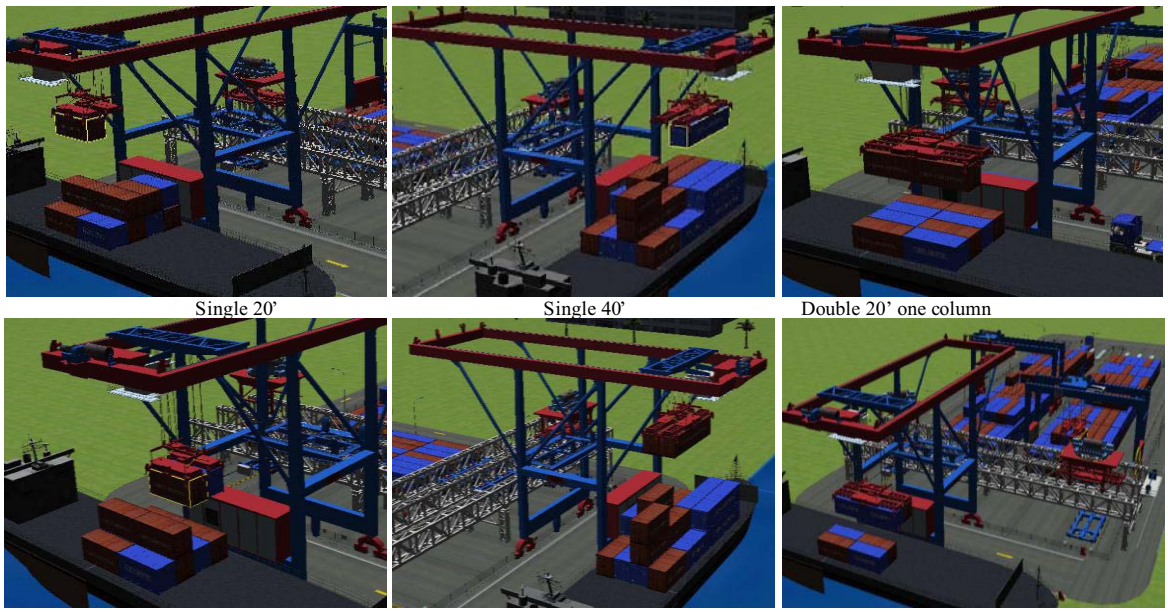

Figure 7. Screenshots of each operation condition

Based on the Virtual Reality platform developed independently by the study team, the CTHT simulation system is built. According to the initialization information, the ZACT chooses the best operating conditions to finish the loading/unloading operation. For the construction of 24 containers (34TEU), ZACT fulfills a total of 12 moves,

the operation conditions utilized are shown in TABLE III. In all of the tasks, six operation conditions are adopted. For example, containers with No. 17,18,19,20 are unloaded at one time with the Four 20' operation condition. Fig. 7 shows each kind of operation condition in the simulation environment.

TABLE III.
SHIP UNLOADING PROCESS

No.	Operation condition	Container No.
1	Single 20'	11;12
2	Single 40'	1;2
3	Double 20' one column	15-16
4	Double 20' two column	13-14
5	Double 40'	3-4;5-6;7-8;9-10
6	Four 20'	17-18-19-20; 21-22-23-24

D. Results and analysis

Since the investment strategy includes adding new port equipment when the port works at full capacity, it was proposed that new loading/unloading vehicles be added where the bottlenecks occur. The special feature of ZACT is that it is composed of twin 40-foot QC, low bridge allocation system and twin 40-foot RMG. Its efficiency has key impact of ACT's operation. In this paper, the efficiency of the key equipments is computed through the simulation. As shown in Fig. 8, the efficiency chart of QC and YCs are calculated as moves/h. The QC's ability in ZACT can reach 25 moves/h, which is equal 100 TEU/h. When comparing to traditional QC (31.38 TEU/h) [12], this greatly improved the efficiency of CT operation.

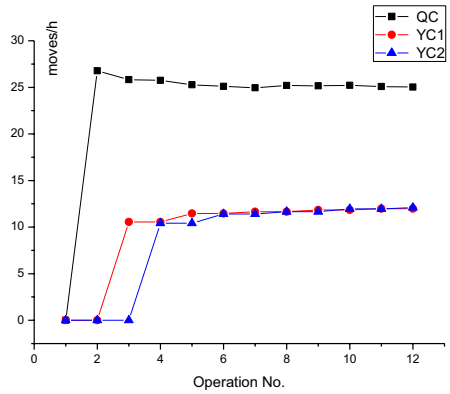

Figure 8. Efficiency chart of QC and YC

In order to better check its validity, some scenarios are simulated here. As shown in TABLE IV, four group instances are provided here. With the given different size container numbers, the operation numbers are got according to the multiple operation condition rules. The key equipment efficiency is provided under each configuration. From the simulation results, it is obvious that Double 40' and Four 20' operation condition have unique advantages in the bid for high working efficiency.

TABLE IV.
SIMULATION RESULTS

TEUs	Containers		ON*.	Efficiency (moves/h)								
	20'	40'		QC	YC1	YC2	LT1	LT2	FT1	FT2	GFT1	GFT2
48	8	20	12	24.7	21.0	21.2	23.4	16.0	22.2	22.2	14.7	12.2
48	0	24	12	25.1	20.6	21.8	18.5	21.8	22.0	22.0	13.9	13.5
48	48	0	12	25.5	20.8	21.4	25.3	24.9	28.7	28.7	14.6	13.8
34	14	10	24	25.0	15.3	15.2	21.3	21.0	30.6	30.6	14.6	13.7

* Operation Numbers: according to the operation conditions rules, the operation numbers generated from the simulation.

V. CONCLUSIONS

The operation of CT is a systematic engineering. It should make overall plans and take all factors into consideration. In the new process of ZACT, the low bridge allocation system cooperate with the twin 40-foot QC and stand two 40-foot containers or four 20-foot containers at once, at the same time, it can satisfy the transportation of double 40-foot RMG, which largely improved the efficiency of the loading and unloading operation. Through the simulation, the efficiency of ZACT can reach 102TEU/h mostly. Comparing with the traditional CT, the operation efficiency increases greatly. This CTHT has a higher value of application and promotion. This method could regard as a decision support tool for analyzing and evaluating port performance for port management. However, the twin 40-foot QC is also subject to various factors and constraints, such as ship size, container ship stowage plan, the configuration of truck/AGVs and terminals management system. This study enriched the contents of CTHT simulation and laid the foundation for further study of ACT.

ACKNOWLEDGEMENT

This research is supported by the National Key Technologies R&D Program of shanghai Science and Technology Commission (project number: 06DZ11202). We also would like to express our acknowledgement to

the R&D department of Shanghai Zhenhua Heavy Industry Co., Ltd. The authors greatly acknowledge useful comments and suggestions for improvement made by anonymous referees on an earlier version of this paper.

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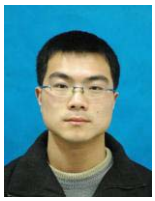

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