

Application of Scheduling Methods in Designing Multimodal In-Vehicle Systems

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ABSTRACT

Multimodal in-vehicle systems (MIVS) may improve time-sharing performance of drivers. However, it is not always clear for designers of MIVS about how to select appropriate modalities and determine the optimal order of messages presented to a driver. To solve this problem, this paper proposes a general procedure to select several scheduling methods (e.g., Johnson's rule and non-identical parallel machine scheduling methods) and uses these scheduling methods to assign appropriate modalities and determine optimal order of messages presented to a driver. An empirical study of an example multimodal in-vehicle system was conducted and it validated the effectiveness of scheduling methods as a tool to improve driver performance and reduce driver workload. Further extensions of the current methodology and usage of this general procedure to select other scheduling methods are also discussed.

INTRODUCTION

IMPORTANCE OF MULTIMODAL IN-VEHICLE SYSTEM DESIGN

With the development of technology, there is increased use of various vehicle information systems (e.g., navigation systems, and vehicle status), vehicle safety/warning systems (e.g., collision warning, pedestrian detection systems), and vehicle communication systems (e.g., cellular phones and vehicle-to-vehicle communication). Multitasking between driving and using these systems may impose high information load on drivers, increasing their mental workload (Alm & Nilsson, 1995; Wagner, Vercruyssen, & Hancock, 1997; Wickens, Kramer, Vanasse, & Donchin, 1983), which in turn increases the chance of vehicle collisions compared to a single driving condition (Alm & Nilsson, 1995; Violanti & Marshall, 1996). This introduces a very important topic in in-vehicle system design and transportation safety—how should in-vehicle systems present information without degrading driver performance and increasing driver workload.

Studies in multimodal user interfaces (MUI) suggest that presentation of concurrent tasks via different sensory channels leads to improved time-sharing performance (Sarter, 2001). For in-vehicle systems, multimodal communication between drivers and in-vehicle systems

might be an effective way to improve driver performance and reduce information overloading in visual modality (Cellario, 2001; Gupta, Bisantz, & Singh, 2002; Mariani, 2002; Siewiorek, Smailagic, & Hornyak, 2002). Several important qualitative guidelines on how to design multimodal user interfaces have been summarized by Sarter (2001). Computational methods for analyzing multimodal information processing have received only scant attention. Little information exists to assist designers of multimodal in-vehicle systems (MIVS) in selecting appropriate modalities and determining the order of presentation of messages based on the properties of the in-vehicle tasks. In other words, if some basic and/or quantitative information of these tasks are given (e.g., their difficulty levels in the cognitive process, their response modalities (hand or body parts), the distance from the body parts to the in-vehicle devices, etc.), the important question becomes how to assist designers of MIVS so that they can follow a list of algorithms to calculate and select the optimal modality and the order of message presentation to drivers.

At an abstract level of analysis, there are two important dimensions to analyze MIVS as a subset of MUI: 1) At the spatial dimension, MIVS designers need to decide which input modalities of drivers will receive information and which output modalities will execute the control actions; 2) At the temporal dimension, drivers receive a sequence of messages from MIVS and execute a sequence of control movements to manipulate the MIVS interface. If information presented to subjects is regarded as "jobs" and the cognitive system is treated as a group of "processors" or "machines" handling these jobs, then scheduling methods—a group of computational methods that deal with how to arrange the order and assignment of the jobs to machines—can be used to quantitatively analyze human information processing in multimodal human-machine interaction.

REVIEW OF SCHEDULING CONCEPTS AND METHODS WITH THEIR APPLICATION IN MUI

Since the 1950s, scheduling has become a major branch of industrial engineering (French, 1982; Pindo, 2002). Depending on a number of machines in a system and measurements of system performance, many scheduling methods and algorithms have been developed in this area. One of the most commonly used performance measurements in scheduling is makespan (C_{max}), defined as the duration between when the first

job arrives and when the last job leaves the system (French, 1982; Pindo, 2002). C_{max} might be the performance measurement most relevant to human performance because it is equivalent to the total task completion time in human performance. Table 1 summarizes several scheduling methods depending on configurations and numbers of machines or processors to minimize makespan (C_{max}) of a system. If machines in a system are arranged in a serial manner (jobs need to go from one processor to another): a) In the single machine condition, since the change of the order of jobs does not affect the makespan, there is no scheduling method developed to minimize C_{max} ; b) When there are two machines or processors arranged in a serial manner, Johnson's Rule is a classic scheduling method to minimize makespan (see description of this rule in detail in the following section of this paper); c) When there are three or more machines, this scheduling problem becomes NP-hard which means there is no polynomial time algorithm to solve it and researchers have to use other methods (e.g., heuristic scheduling methods) to solve these scheduling problems (see (Pindo, 2002) for detailed description of heuristic scheduling methods). In the parallel arrangement situation, depending on the number of processors in a system, the parallel scheduling method (French, 1982) and critical path analysis have been proposed to solve the scheduling problem (see a review of critical path analysis method in (Harold, 2001)). In the field of multimodal user interface, it seems that only critical path analysis has been used to design multimodal user interface (MUI) (see a review of critical path analysis method in designing MUI in (Baber & Mellor, 2001)) while other simple but effective

scheduling methods, including Johnson's Rule, have not been applied, especially to in-vehicle systems.

RELATIONSHIP BETWEEN C_{MAX} (PERFORMANCE) AND SUBJECTIVE DRIVER WORKLOAD

The specific usage of multimodal systems in vehicles and the measurement of subjective driver workload suggest a specific relationship between subjective mental workload and the total in-vehicle task completion time. In driving experiments, the data of subjective workload can only be collected after a driver drives for a certain amount of time with at least several trials of an in-vehicle task; otherwise he or she will not have enough time to experience the workload in using the in-vehicle system.

If we regard the whole cognitive system as a server that processes information from both a road and an in-vehicle system, there is a direct proportional relationship between utilization of this server (ρ) and subjective driver workload (WL) (Wu & Liu, In Press):

$WL = a\rho + b$ (1)

where a and b are constants depending on different driving situations and in-vehicle systems ($a > 0$). In queueing network theory, utilization (ρ) of a single server can be quantified using the following equation:

$\rho = \lambda/\mu$ (2)

TABLE 1 Summary of Scheduling Methods to Minimize Makespan (C_{max}) of a System

Configuration	Number of Machines	Scheduling Methods	Application in MUI
Serial	Single machine	-	-
	Two machines	Johnson's Rule ¹	Not yet
	Three or more machine	NP-Hard (Heuristic approaches)	-
Parallel	Two or more machines (machine number < job number)	Non-Identical Parallel Machine Scheduling Method ²	Not yet
	Infinite number of machines	Critical Path Analysis	(Baber & Mellor, 2001)
	(machine number > job number)		

1. Johnson's Rule: Johnson (1954) proposed an optimal scheduling method to arrange the sequence of jobs entering a system in which two machines are arranged in a serial order. The optimal sequence can be obtained by partitioning the jobs into two sets, with Set I containing all the jobs with p_{1j} (processing time of job j on machine 1) $< p_{2j}$ and Set II all the jobs with $p_{1j} \geq p_{2j}$. The jobs in Set I go first, in increasing order of p_{1j} ; the jobs in Set II follow in decreasing order of p_{2j} (Johnson, 1954).

2. Non-Identical Parallel Machine Scheduling Method: Sule (1996) proposed a scheduling method to assign jobs to machines in parallel with different processing times as well as to arrange the order of jobs entering these machines. This method includes three steps (Sule, 1996). Step 1: Rank the m parallel machines such that the most efficient machine (the one taking the least amount of time to process) is machine 1, the next efficient machine is machine 2, and so on. We can also rank the jobs in descending order of processing times, indicating the job with the largest processing time as job 1, the job with the next longest processing time as job 2, and so on. Step 2: Add the processing times of all jobs on machine 1. This is the current value of TT_1 (total of processing times assigned to machine 1). TT_i for $i=2,3,...,m$ is 0, because no jobs are assigned to machine 2 through m . TT_1 is the present value of the makespan. Step 3: Examine the feasibility of reassignment of jobs starting with the first job and proceeding toward job n . To do so, first select the candidate job. Temporarily remove it from machine 1 and assign it to all remaining machines. Reduce the value of TT_1 by the processing time of the candidate job. Increase TT_i for machine i by the associated processing of the job on that machine and determine the minimum value of TT_i for $i=2,...,m$ (except ignore $TT_i = 0$). The associated processor is where the job should be assigned if it is to be moved from machine 1. Compare the minimum of TT_i with TT_1 and determine the lower value of the two. If the new value of the makespan is less than the present value of the makespan, make the new assignment permanent and assign the makespan the new value. If the new makespan is not less than the present makespan, the reassignment of this job is rejected. Select the next job in the sequence and repeat the step. If all jobs are examined, stop; we have the best assignment.

where λ is the arrival rate of information and μ is the processing speed of the server. Since C_{max} is the total task completion time in each trial using the in-vehicle system, it is in inverse proportion to the processing speed of the cognitive system, i.e.:

$$\mu = 1/C_{max} \quad (3)$$

Combining the equations above, we can easily derive:

$$WL = a\lambda C_{max} + b \quad (a > 0) \quad (4)$$

which indicates a directly proportional relationship between makespan (C_{max}) and subjective driver workload. In other words, scheduling algorithms that minimize C_{max} might also be used to reduce the subjective driver workload under the condition that the arrival rate of information remains the same.

A GENERAL PROCEDURE TO SELECT THE SCHEDULING METHODS IN MIVS

Based on the Theory of Constraints (TOC) and general procedure of applying scheduling methods in practice (McMullen, 1998; Pindo, 2002), a general procedure was proposed to select and use scheduling methods in designing MIVS. In addition, in order to illustrate the procedure clearly, the following definitions were used:

STEP 1. IDENTIFY STATUS OF A INFORMATION PROCESSING STAGE

The following rules can be used to determine the serial or parallel processing at each processing stage (perceptual, cognitive, and motor stages). Each job/task to be analyzed first needs to be decomposed into one, two, or three of the three major stages of information processing. Second, it is necessary to identify the information processing status of each stage is serial or parallel. For example, if one of the three stages can process information at the same time (e.g., the right hand is operating an in-vehicle device while the right foot is pressing a break), this stage can be regarded as a parallel stage (PS). On the other hand, if a stage can only handle the information/jobs one by one, this stage is regarded as a bottleneck stage (BS) (e.g., in the cognitive stage, subjects can only perform one arithmetic problem at one time; Pashler, 1984).

STEP 2. CHOOSE THE CORRESPONDING SCHEDULING METHODS AND SCHEDULE THE JOB AT EACH STAGE

Once the status of a stage is identified (BS or PS), the second step is to select the scheduling methods to arrange the order of jobs based on following rules:

1) 1 BS (there is only one BS in the cognitive system based on the current task setting)
If PS (Number of PS ≥ 1) is identified in the system:
→ Use Non-Identical Parallel Machine Scheduling Method to schedule each PS
Else: No scheduling method is recommended for this situation since change of job orders will not affect C_{max} and workload
2) 2BS (there are two BS in the cognitive system based on the current task setting)
2BS+1 PS: Use Non-Identical Parallel Machine Scheduling Method to schedule the PS
If the 2 BS are connected directly → Use Johnson's Rule
Else → Only schedule the PS using Non-Identical Parallel Machine Scheduling Method
Only 2BS: → Use Johnson's Rule
3) 3BS: Use heuristic scheduling methods
4) 0 BS: No scheduling method is recommended for this situation since change of job orders will not affect C_{max} and workload

STEP 3. REARRANGE THE ORDER OF JOBS OR/AND REASSIGN THE JOBS TO AVOID INCONSISTENCY

Step 2 may generate different job orders or different assignment of jobs in different stages. If this happens, considering the nature of human information processing, changing the order of jobs within the cognitive system may increase incompatibility between the stimuli order and the order of mental and/or motor processing, causing extra load on the cognitive system (Kok, 2001). Therefore, it is recommended to keep the order and assignment of jobs the same with the scheduling results (job orders and assignment of jobs) of the stage with longest processing time which can be estimated via GOMS (Goal, Operators, Methods, Selection) (Olsen & Olsen, 1990), MHP (Model Human Processors) (Card, Moran, & Newell, 1983), or QN-MHP (Wu & Liu, In Press).

STEP 4. VALIDATE THE SCHEDULING RESULTS WITH SIMULATION OR EXPERIMENT AND DESIGN THE MIVS BASED ON THE VALIDATED SCHEDULING RESULTS

The following section describes a case study in using the scheduling methods and procedure to select optimal modality and job orders when drivers are operating a multimodal in-vehicle system.