Automatic Driving System Based on Embedded Microcontroller Using Human Skill Models

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***Abstract*—in the previous work, the authors proposed an efficient method to abstract human skill based on HHARX model, and successfully applied the obtained human skill models in an automatic driving system of a radio-controlled vehicle based on PC. This paper proposes a method to reconstruct the driving system based on embedded microcontroller OMAP3530. In the system, Omap3530 realize all the control functions except for model identification, such as real time image collection and processing, obstacle position detection, automatic driving environmental parameters computing, driving control commands computing using human driving skill models, radio-controlled vehicle real time driving control, and so on. The obtained driving system can drive the small radio-controlled vehicle automatically without PC according the human driving skill models, the flexibility and area of application of human skill models can be improved efficiently.**

***Index Terms*—human skill model, automatic driving system, real time image collection, real time image processing, radio-controlled vehicle, embedded microcontroller**

I. Introduction

Driving a vehicle is a complex activity. Drivers need important knowledge to avoid all kinds of accidents. However, the target is difficult to be achieved for different conditions. For example, driving skill of older drivers has been found to decline with age [1], while novice drivers detect hazards less quickly compared to experienced drivers [2]. Therefore, for driving safety, an automatic driving system or a driving assistance system is needed, which can achieve automatic driving or give advice about risks and opportunities during the driver's activity. For the purpose, many researchers focus their attention on finding good driving models [3] [4].

In many fields such as industrial production, motor vehicle driving, musical instrument playing, human have accumulated extensive experience of manipulation. If manipulation skills of skilled operators can be abstracted as a model and transferred into industrial robots or automatic controllers, we can construct an automatic operating system or an appropriate operating assistance system, such that not only safety, but also efficiency of manipulation can be improved. For the reason, recently, modeling of human manipulation skill in complex and various tasks is actively researched. Many studies demonstrated the significance of research in this field.

For example, in the field of aerial navigation, an automatic landing system has been developed on the basis of a human skill model, and the model is expressed as a nonlinear I/O mapping from the aircraft state to the control command provided by a human expert [5]. For robot balance control, a human control strategy model has been trained to abstract the operator’s skill in controlling the tilt-up motion, and then a human-based controller has been developed such that the robot can recover from fall automatically [6]. For modeling human sport action, human skills in dynamic manipulations have been investigated and have been applied to a golf swing robot [7], and so on.

Up to now, great amounts of modeling methods have been proposed in numerous literatures for different types of dynamical systems. For human skill modeling, because of the lack of good physical models for human skill, it is impossible to model it from physical or chemical principles of a system. Therefore, many researchers focus their attention on system identification while modeling human manipulation skills [8] [9] [10] 11].

In literatures [10] and [11], the authors proposed an efficient approach to abstract human manipulation skill, which can be useful in systems of machine intelligence and human operator assistance. The approach is to consider human manipulation skill as a hybrid dynamical system (HDS). Specially, a hinging hyperplane autoregressive exogenous (HHARX) model is utilized as it is able to deal with manipulation modes and their switches simultaneously. The authors obtain the HHARX model by system identification via mixed-integer linear programming (MILP). As a typical example, they apply their approach to an automatic driving system of a small radio-controlled vehicle. Both simulation and

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experimental results illustrate the effectiveness of the proposed method.

However, up to now, most application of human skill models are based on PC, such as the application of human driving skill models in automatic driving system [10] [11]. That is both real time image collection and vehicle control according to human driving skill models are carried out based on PC, which limited the flexibility of the application of human skill models. For the reason, in this paper, the authors propose a method to realize the human driving skill models based on embedded microcontroller OMAP3530. In the system, Omap3530 realize all the control functions except for model identification, such as real time image collection and processing, obstacle position detection, automatic driving environmental parameters computing, driving control commands computing using human driving skill models, radio-controlled vehicle real time driving control, and so on. The obtained driving system can drive the small radio-controlled vehicle automatically without PC according the human driving skill models, the flexibility and area of application of human skill models can be improved efficiently.

II. Experimental environment

To obtain the model of human driving skill, in the previous works [10], [11], a video camera, a computer and some related image processing software are used to construct an experimental environment, which is shown in Fig. 1. In Fig. 1, the small radio-controlled vehicle on the route (hereafter, simply, "vehicle") have six driving modes: "right turn", "left turn", "forward", "backward", "acceleration" and "deceleration". When a person drives the vehicle along the route via a remote controller, the positional information of the vehicle is captured by the video camera and is sent to the computer in real-time. The saved data of the positional information of the vehicle is the raw data for system identification to obtain human driving skill models. On the other hand, while apply human driving skill models to an automatic driving system in the environment as shown in Fig. 1, the captured real time image data is sent to PC, PC calculate driving environmental parameters using the image data and driving commands according to human driving skill models, and then carry out auto driving.

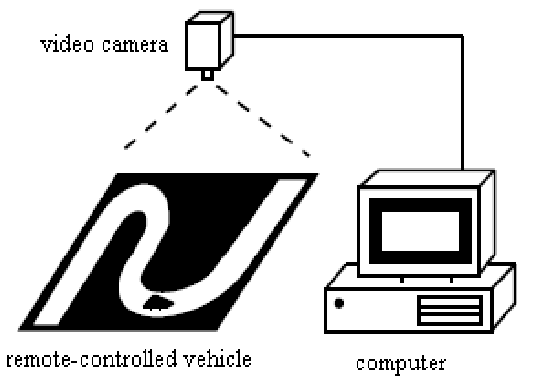


Figure 1. Experimental environment based on PC

In this paper, to improve the flexibility and extend application area of human driving skill models, such as outdoor environment without PC, driving environment without fixed driving route, and so on, we propose to replace the PC in Fig. 1with an embedded microcontroller OMAP3530. TI's OMAP3530 represents the first broad-market application of the ARM Cortex-A8 processor core, combining this with a DM64x class video/audio DSP capable of HD video, a PowerVR graphics module with OpenGL ES 2.0 support, and a rich set of interfaces as well as ETM/Coresight debug. The reestablished experimental environment based on OMAP3530 is able to construct a miniature automatic driving system.

Structure chart of automatic driving system based on OMAP3530 is shown in Fig.

In Fig. 2, OMAP3530 captures driving environmental image and takes image processing in real time, recognizes driving route and roadblocks, calculates distances between the vehicle and roadblock or route side firstly. Then, according to obtained information, OMAP3530 calculates driving commands by using human driving skill models and takes automatic driving control according to the driving commands in real time. The real time driving information of the radio-controlled vehicle should be feedback to the controller to correct driving commands slightly.

III. Human driving skill models

Automatically driving a vehicle in a given environment, such as in Fig. 1 or its reestablished environment based on OMAP3530, should be able to determine steering angle and velocity commands input to the vehicle according to distances between the vehicle and the route sides or roadblock and so forth. To achieve the basic demand, a function from y_t to u_t is considered, where y_t and u_t are output of the environment about the vehicle and input to the vehicle, respectively. The output of the environment y_t includes v_t, v_{t-1}, a_t, d_{1t}, d_{2t}, d_{3t}, and so on. Here, v_t and a_t are velocity and steering angle of the vehicle at sampling time t, respectively. v_{t-1} is the velocity of the vehicle at sampling time $t-1$, d_{1t}, d_{2t} and , d_{3t} are distances from the vehicle to the left, to the right and to the front side of the route, respectively. d_{1t} and d_{2t} are calculated in the directions of right and left 30[deg] based

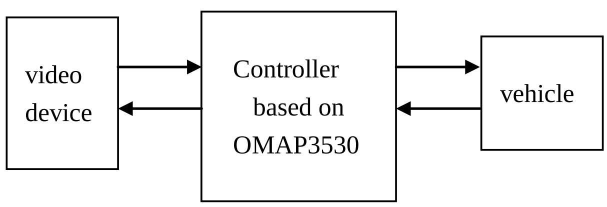


Figure 2. Structure chart of automatic driving system based on OMAP3530

on the traveling direction of the vehicle. On the other hand, the input to the vehicle includes u_{1t} and u_{2t} which are velocity command and steering angle command to the vehicle, respectively.

For simplicity, the human driving skill models consist of two separate models: steering angle control model and velocity control model, and both models of steering angle controller and velocity controller are assumed to be functions of y_t.

When the vehicle is driven along the route, there exist several operation modes, such as "right turn", "left turn", "forward", "backward", "acceleration" and "deceleration". In addition, several switch points of the operation modes are also exist. Therefore, each controller of the automatic driving system of the vehicle is expressed as a HDS, where each continuous submodel deals with its related manipulation mode, while a discrete event model represents the switches between all the submodels. We assume that the HDS model of each controller has an HHARX structure with an appropriate number of switch points. That is, the model has the form

$$f(\varphi_t,\theta)=\varphi_t^{'}\theta_0+\sum_{i=1}^{M}s_i\min\left(\varphi_t^{'}\theta_i,0\right) \tag{1}$$

In (1), M is the number of switch points of a hybrid dynamical system, $\varphi_t\left(t\in \mathrm{T}:=\{1,2,\cdots,N\}\right)$ and $\theta_i\left(i\in \mathrm{I}:=\{1,2,\cdots,M\}\right)$ are regression vectors and parameters, respectively, N is the number of data. For human driving skill models, M is number of driving modes besides driving forward.

Note that $f(\varphi_t,\theta)$ is treated as both steering angle controller and velocity controller. Parameter θ in (1) is given by solving the following optimization problem [12].

$$\theta^{*}:=\arg\min_{\theta}\sum_{t=1}^{N}\left|u_t-f(\varphi_t,\theta)\right| \tag{2}$$

In (2), $u_t(t\in\Gamma:=\{1,2,3......,N\})$ is the measured data, $f(\varphi_t,\theta)$ is the output value of the model. For a hybrid dynamical system such human driving models, optimal parameters θ^{*} include information of both switch points of submodels and parameters of each submodel.

In (2), HHARX model $f(\varphi_t,\theta)$ is nonlinear. Moreover, the absolute value should be calculated. Therefore, the optimization problem in (2) is a complicated nonlinear problem.

To recast (2) as simple linear problems, especially as an MILP problem, for which some efficient solvers exist, introduce new 0-1 auxiliary variables δ_{it}:

$$\left[\delta_{it}=1\right]\leftrightarrow\left[\varphi_t^{'}\theta_i\le 0\right],\left(i\in\Gamma,t\in\Gamma\right) \tag{3}$$

continuous variables z_{it}:

$$z_{it}=\min\left(\varphi_t^{'}\theta_i,0\right)=\varphi_t^{'}\theta_i\delta_{it} \tag{4}$$

and the auxiliary slack variables ε_t:

$$\varepsilon_t\ge\left|u_t-f\left(\varphi_t,\theta\right)\right|,\left(t\in\Gamma\right) \tag{5}$$

Equations (3), (4) and (5) can be transformed into mixed-integer linear inequalities [12]:

$$\begin{cases} z_{it}\ge m_{it}^{\theta}\delta_{it} \\ z_{it}\le\varphi_t{'}\theta_i \\ \left(1-\delta_{it}\right)M_{it}^{\theta}+z_{it}\ge\varphi_t{'}\theta_i \\ \varepsilon_t\ge u_t-\varphi_t{'}\theta_0-\sum_{i=1}^{M}s_iz_{it} \\ \varepsilon_t\ge -u_t+\varphi_t{'}\theta_0-\sum_{i=1}^{M}s_iz_{it} \\ z_{it}\le 0,\varepsilon_t\ge 0,\left(i\in\mathrm{I},t\in\Gamma\right) \end{cases} \tag{6}$$

In (6), M_{it}^{θ} and m_{it}^{θ} are upper and lower bounds on $\varphi^{'}\theta_i$, respectively.

Under the new auxiliary variables and constraints, the optimum of problem (2) is equivalent to that of the MILP

$$\theta^{*}:=\arg\min_{\varepsilon_t,\theta_t,z_{it},\delta_{it}}\sum_{t=1}^{N}\varepsilon_t \tag{7}$$

subject to inequalities (6) and

$$\delta_{it}\in\{0,1\},\theta_i^{-}\le\theta_i\le\theta_i^{+},\left(i\in\mathrm{I},t\in\Gamma\right) \tag{8}$$

In (7), M, N, φ_t, s_i, M_{it}^{θ} and m_{it}^{θ} are given, while ε_t, θ_i, z_{it} and δ_{it} are variables to be optimized. The identification problem is much harder if the number of switch points M is unknown.

For more detailed description about hybrid dynamical system identification via mixed-integer linear programming, see literature [12]. And for more detailed description about abstraction of human driving skill, see literatures [10] and [11].

In this paper, considering both processing capacity of embedded microcontroller OMAP3530 and minimal requirements for human driving skill modeling, M is set to 2 corresponding driving modes left turn and right turn, N is set to 20. Before constructing automatic driving system of a radio-controlled vehicle, human operation skill for driving the vehicle through a remote controller is identified offline on PC based on the experimental environment shown in Fig. 1. The next section describes the design of controller of automatic driving system using the obtained human driving skill models based on OMAP3530, including hardware design and embedded software design.

IV. CONTROLLER DESIGN BASED ON OMAP3530

Most video collection products are thin client mode, that is, video capture terminal only carry out image collection and simple image coding and then sends image data to PC for processing [13] [14]. For application of human driving skill models in this mode, image should be captured and be sent to PC for processing, and then the processing results should be sent to controller of the automatic driving system, all these should be done in real time. Therefore, the cost of communication is high and application flexibility of human skill models is limited.

For the purpose, the authors proposed a method to collect and process real time image by OMAP3530 [15]. This paper proposes a new application mode for human skill models, replace PC in original system with an embedded microcontroller to construct a miniature automatic driving system. Therefore, in the reconstructed system, both real time image captures, processing and vehicle control based on human driving skill models is carried out by a single OMAP3530, so the flexibility of application of human skill models can be improved.

A. Hardware design based on OMAP3530

The structure chart of automatic driving system using OMAP3530 is shown in Fig. 3. In Fig. 3, OMAP3530 is an embedded microcontroller, which includes ARM core and DSP core in a signal ship. OMAP3530 collect real time image by camera interface firstly, then combining distance measuring results of ultrasonic ranging module calculate real time driving status information, such as driving speed, driving direction, distances between the small radio-controlled vehicle and the barriers. Next, according to human driving skill models, OMAP3530 generate automatic driving commands to drive the small radio-controlled vehicle through a driving module. Moreover, OMAP3530 receives real time speed and direction information of the vehicle from the driving module correct automatic driving commands slightly. Bluetooth communication interface is used to information exchange between OMAP3530 system and computer, so except for automatic driving based on OMAP3530 the vehicle can also be controlled by a computer directly.

The structure chart of driving module in Fig. 3 is shown in 4. Driving module receives driving commands from OMAP3530, generates electric current signal according to the driving commands, amplifies the signals and transmits to servo motors. To improve auto driving effect, an ultrasonic ranging system is also included in the servo driving system, which measure the distances between the vehicle and roadblock in real time, the measuring result is used to correct the image processing result. Speed measuring module measure running speed of the right wheel and the left wheel in real time, which is used to correct steering angle control.

Moreover, automatic driving system should include memory interface, such as USB device, CF card, ST card, and so on. Picture of the constructed real system including controlled vehicle is shown in Fig. 5. In Fig. 5, the vehicle is a reconstructed radio-controlled vehicle, beside OMAP3530 control center, system including ultrasonic ranging module, servo driving module, speed and driving direction measuring module memory module, communication module, and so on. The automatic driving system is powered by a mobile phone battery.

Based on the hardware, the control flow for automatic driving is shown in Fig. 6. In Fig. 6, identification of human driving skill is done by PC offline and the automatic driving of the small radio-controlled vehicle is done by OMAP3530 online. More detailed description about identification of human driving skill, see literatures [10] and [11]. The next subsection will describe the

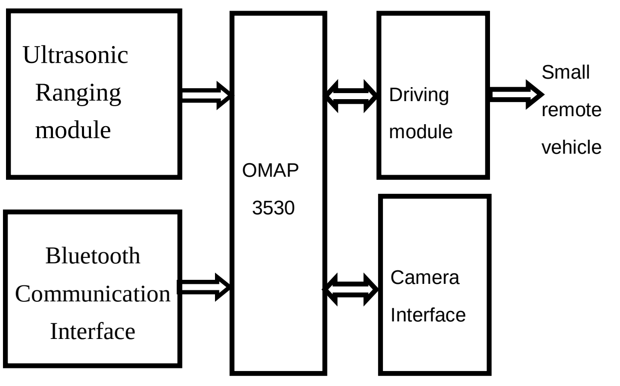


Figure 5. Structure of automatic driving system

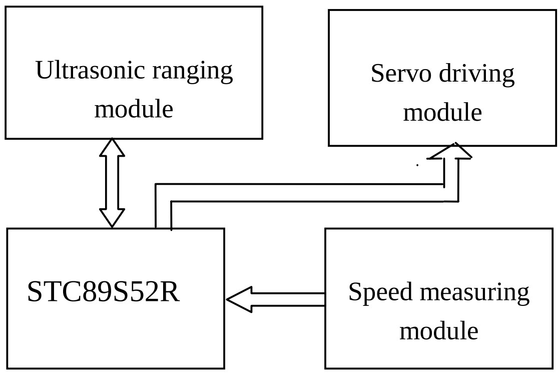


Figure 3. Servo driving system

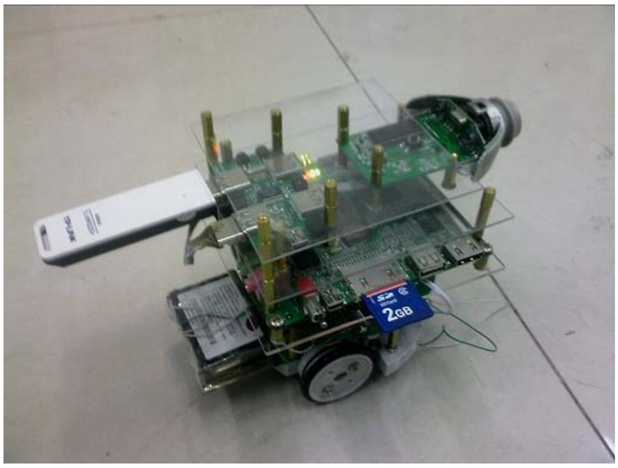


Figure 4. Picture of real system including controlled vehicle

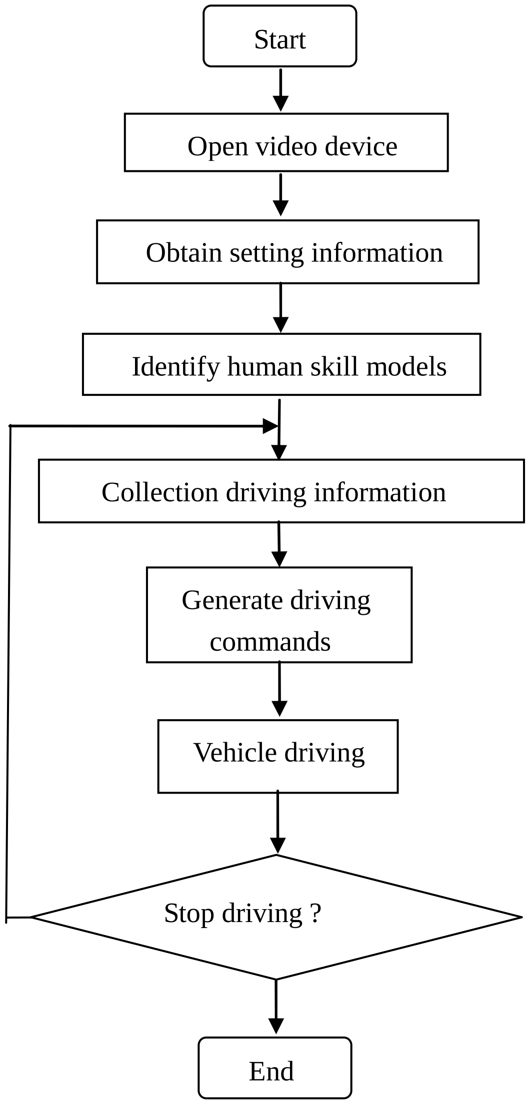


Figure 7. Control flow of automatic driving by OMAP3530

design and realization of embedded software system of the automatic driving system based on OMAP3530.

B. *Embedded softwrae design based on OMAP3530*

In Fig. 6, to auto drive the small radio-controlled vehicle, driving information of the vehicle should be obtained in real time. To achieve the purpose, after adding OV511 driving program in Linux core by core recompiling, image collection programming is done by using video4linux. Video4Linux is intended to provide a common programming interface for the many TV and capture cards now on the market, as well as parallel port and USB video cameras. Radio, teletext decoders and vertical blanking data interfaces are also provided. The flow chart of real time image collection by OMAP3530 is illustrated in Fig. 7.

In Fig. 7, the image processing module position objectives and give information to video saving and driving commands computing modules for automatic driving. Real time image processing flow is shown in Fig. 8.

In Fig. 8, the original image is captured by a video camera, and then via a median filter Gaussian noise of the captured image is removed, firstly. Next, the image Soble edge detection is done to obtain edge information of the object. Thereafter, through large-scale morphological dilation operation and same-scale corrosion operation, the

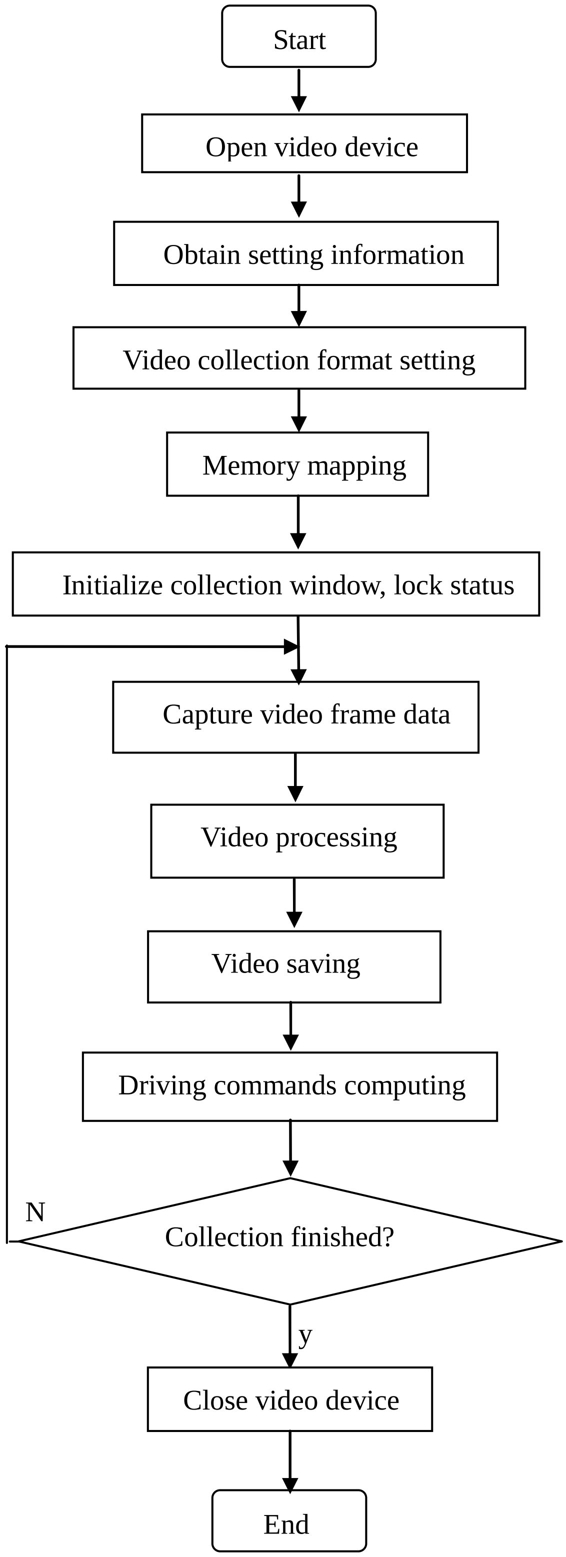


Figure 6. Flowchart of real time image collection by OMAP3530

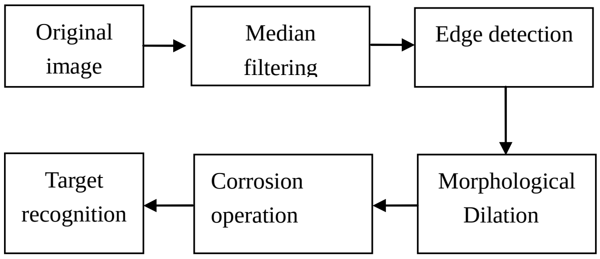
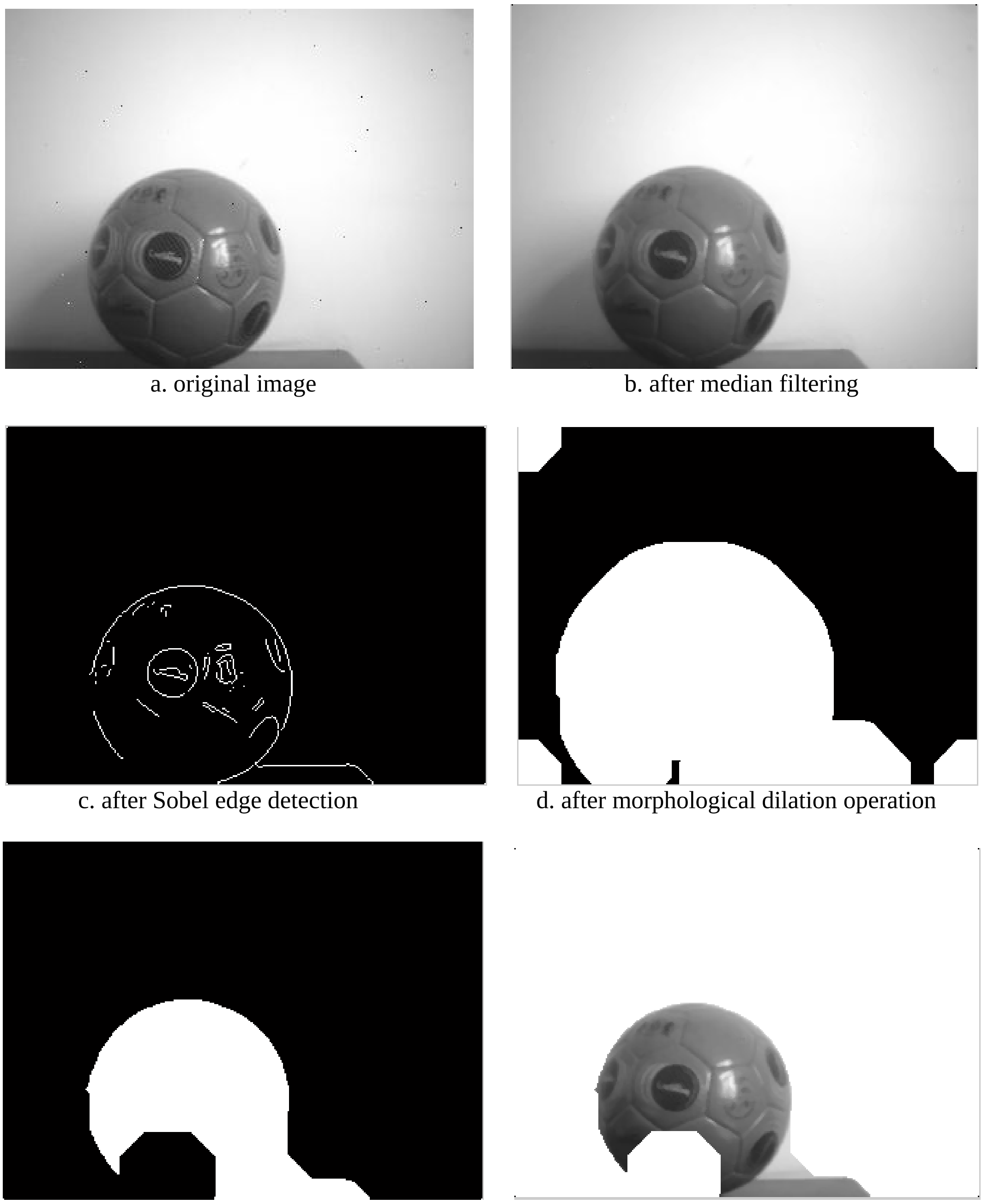


Figure 8. Image processing flow by OMAP3530

basic outline of the object can be obtained. Finally, target identification and positioning can be dong via some appropriate algorithms. Real time image processing results are shown in Fig. 9.

In Fig. 8, for edge detection, the Sobel operator is used firstly. Technically, it is a discrete differentiation operator, computing an approximation of the gradient of the image intensity function. At each point in the image, the result of the Sobel operator is either the corresponding gradient vector or the norm of this vector. The Sobel operator is based on convolving the image with a small, separable, and integer valued filter in horizontal and vertical direction and is therefore relatively inexpensive in terms of computations. On the other hand, the gradient approximation which it produces is relatively crude, in



a. original image b. after median filtering

c. after Sobel edge detection d. after morphological dilation operation

e. after morphological corrosion operation f. result of target identification

Figure 9. Image processing results by OMAP3530

particular for high frequency variations in the image.

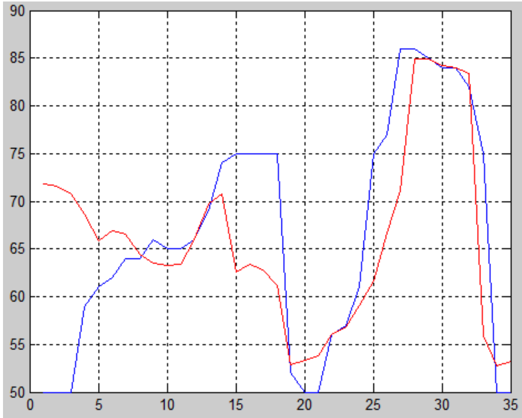
The Sobel operator is based on convolving the image with a small, separable, and integer valued filter in horizontal and vertical direction. Many application of Sobel operator is based on PC and in the general C code of its convolving function, image data is stored as a $M \times N$ matrix. While apply the C code of convolving function to OMAP3530, to improve processing speed, image data is stored as a vector, so some corrections of C code are done in [16].

C. Automatic driving based on OMAP3530

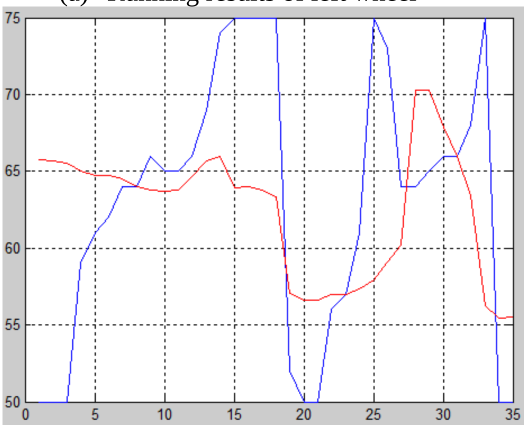
Based on the image processing results, combining distance measuring results of ultrasonic ranging module, OMAP3530 calculate information for human driving skill model identification or application, such as v_t, v_{t-1}, a_t, d_{1t}, d_{2t}, d_{3t}, and so on, where d_{1t}, d_{2t} and d_{3t} are distances between the small vehicle and driving route or roadblock in different direction, v_t and v_{t-1} are driving speed at sampling time t and $t-1$, a_t is acceleration of the vehicle.

In the stage of human driving skill modeling, model identification is done on PC off line by using the calculated information. On the other hand, in the stage of auto driving, by using the obtained human driving skill models, operating commands are calculated by OMAP3530 in real time firstly, such as driving speed command u_{1t} and steering angle command u_{2t}. Then, according to and u_{1t} and u_{2t}, servo driving module generates real driving control signal in real time to realize the automatic driving of the radio-controlled vehicle.

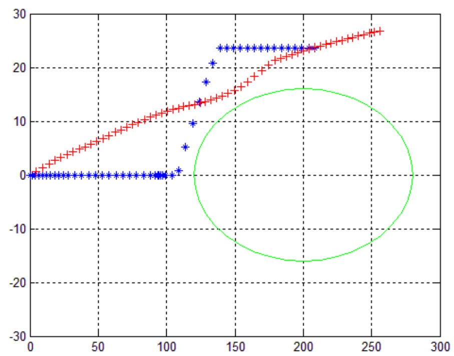
By using the automatic driving system based on OMAP 3530, auto driving is done, riving results shown in Fig. 10. In Fig. 10, blue lines are driving results by a person through a remote controller, and right lines are automatic driving results by the obtained human driving skill models based on OMAP3530. Experimental results illustrate that the vehicle can recognize driving route and roadblock automatically and then auto driving according to human driving skill models. However, real recognition rate of roadblock is not very satisfied and driving speed should be limited to low level. Main reason is that the OMAP3530 is a new device of TI, its performance of DSP core of OMAP3530 has not been fully exploited. This is our future research tasks.



(a) Running results of left wheel



(b) Running results of right wheel



(c) Automatic driving results

Figure 10. Experimental results

VI. Conclusion

This paper proposed an application mode of human driving skill model to construct a miniature automatic driving system based on OMAP3530. In the system, image collection, processing and vehicle driving control according to human driving skill models can be carried out based on a single embedded microcontroller OMAP3530 in real time, so the flexibility of application of human skill models can be improved efficiently. As the future research tasks, performance of DSP core of OMAP3530 should be exploited sufficiently to improve image processing effect and then automatic driving results.

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