

Sensorless PMSM Field-Oriented Control on Kinetis KV31 with FreeRTOS & eGUI

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1. Introduction

This application note describes the implementation of the sensorless Motor Control Reference Solution Package (MCRSP) software for a 3-phase Permanent Magnet Synchronous Motor (PMSM) with the FreeRTOS OS (including the motor-parameters identification algorithm) on 32-bit Kinetis V series MCUs. The communication is provided by FreeMASTER. The sensorless control software itself and the PMSM control theory in general are described in *Sensorless PMSM Field-Oriented Control* (document [DRM148](#)) and *Sensorless PMSM Field-Oriented Control on Kinetis KV* (document [AN5237](#)). The LCD display shield is used to show the application states and the current motor speed on gauges. The demo mode is controlled using either the on-board push-button or the FreeMASTER control page that also supports on-line application monitoring and debugging.

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1.1. Description

The purpose of this application note is to describe the motor-control part implementation with the FreeRTOS OS.

This application note covers:

- Overview and important details
- Basic introduction to the FreeRTOS OS
- Implementation of the motor-control part and the FreeRTOS OS
- Interrupt control

This application note doesn't describe:

- Full description of the FreeRTOS OS (all functions)
- Detailed PMSM motor control (can be found in *Sensorless PMSM Field-Oriented Control* (document [DRM148](#)))
- Detailed description of eGUI (can be found in *Freescale Embedded GUI (D4D)* (document [DRM116](#)))

2. Hardware Requirements

The development platform chosen for the embedded application is the NXP Freedom FRDM-KV31F board populated with the KV3x family MCU, the FRDM-MC-LVPMSM board for driving 3-phase low-voltage PMSM motors, and the Arduino™ R3-compatible LCD TFT shield driven by the SPI signals and the on-board graphical IC HX8347.

2.1. FRDM-KV31F

The KV31F MCU family is a highly-scalable member of the Kinetis V series and provides a high-performance, cost-competitive, motor-control solution. It is built around the ARM® Cortex-M4® core running at 120 MHz with up to 512 KB flash and up to 96 KB RAM, combined with the floating-point unit. It delivers a platform that enables the customers to build a scalable solution portfolio. The additional features include dual 16-bit ADCs sampling at up to 1.2 MS/s in a 12-bit mode, 20 channels of flexible motor-control timers (PWMs) across four independent time bases, and a large RAM block that enables local execution of fast control loops at full clock speed. For more details, see *KV31F Sub-Family Reference Manual* (document [KV31P100M120SF7RM](#)).

The NXP Freedom KV31F board is a powerful, low-cost development platform targeted for low-voltage motor-control applications. The board combines the main KV31F MCU, a micro-USB connector with a compatible debugger, and four headers where the outer columns have Arduino-compatible signals (the inner columns are intended for the NXP Freedom evaluation boards). The signal routing can be found in the particular scheme or application note for the specific evaluation board. The main NXP Freedom board can be mounted with various motor-control shields, such as FRDM-MC-LVPMSM for driving low-voltage PMSM motors or FRDM-MC-LVBLDC targeted for low-voltage BLDC motors.

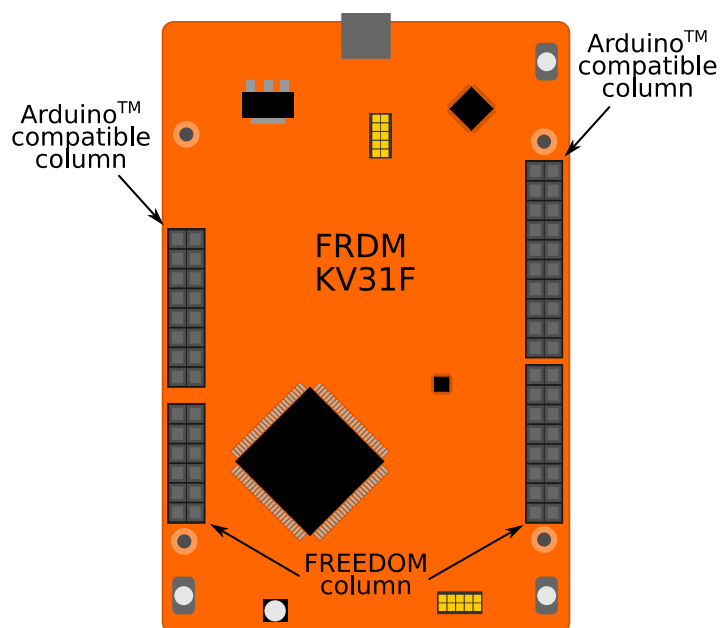


Figure 1. KV31 NXP Freedom development platform

2.2. FRDM-MC-LVPMSM

Evaluation board (in a shield form factor) turns an NXP Freedom development board into a complete motor-control solution compatible with the FRDM-KV31F NXP Freedom development board. The NXP Freedom motor-control headers are compatible with the Arduino R3 pin layout on the outer columns. The module enables stacking other compatible boards on top of the pin headers (this can be used to extend the application functionality).

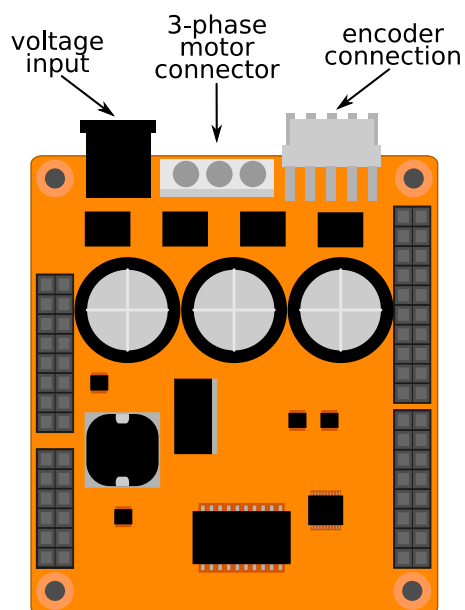


Figure 2. PMSM evaluation board

The FRDM-MC-LVPMSM board has a power supply input voltage of 24-48 VDC with a reverse-polarity protection circuitry. An auxiliary power supply of 5.5 VDC is used to provide power for the FRDM MCU boards. The output current ranges up to 5 A RMS. The inverter itself is realized by a 3-phase bridge inverter (6-MOSFET) and a 3-phase MOSFET gate driver. Analog quantities (such as the 3-phase motor currents, DC-bus voltage, and DC-bus current) are sensed on this board. There is also an interface for speed/position sensors (Encoder, Hall). The block diagram of a complete NXP Freedom motor-control development kit is shown in this figure:

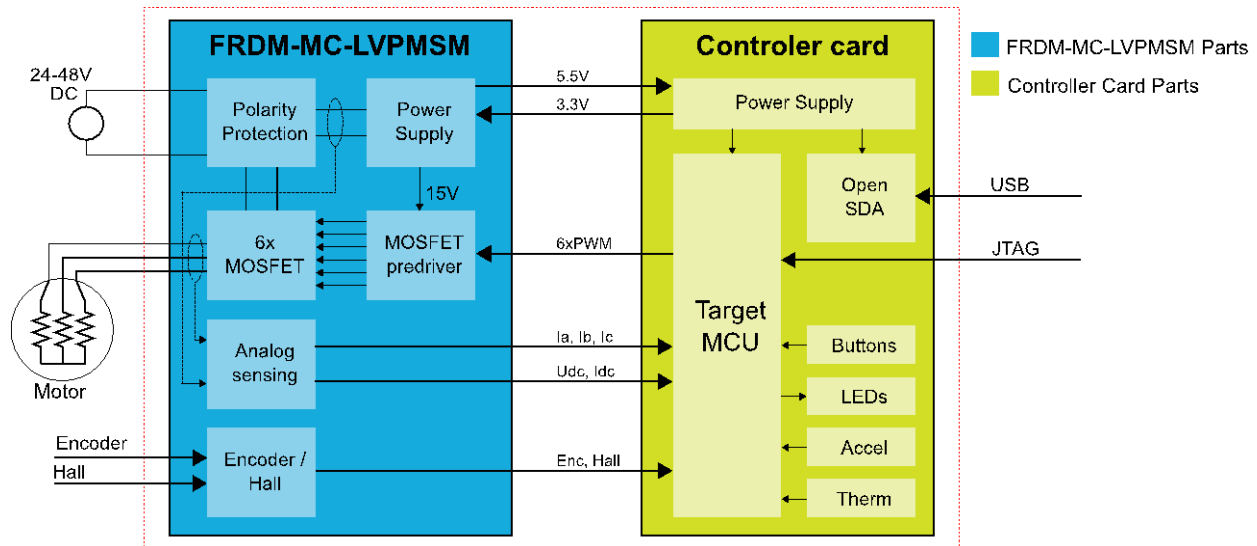


Figure 3. NXP Freedom motor-control development platform block diagram

The FRDM-MC-LVPMSM does not require any complicated setup and there is only one way to connect this shield board to the NXP Freedom MCU board. See *PMSM Control Reference Solution Package* (document [PMSMCRSPUG](#)). For more information about the NXP Freedom development platform, see www.nxp.com.

2.3. Arduino LCD TFT shield

The LCD TFT display turns the embedded demo application into a user-friendly platform which displays the application states and other required parameters or values in real time. For these purposes, an Arduino-compatible display shield that contains a graphical driver for driving a 320x240 display with mounted voltage regulators and backlight control is used. The board also contains support for touch sensing and has an SD card slot; both can communicate via SPI. The following figure shows the available pins used on the board. The method of display operation is described in [Section 5.1](#), “Graphical library”.

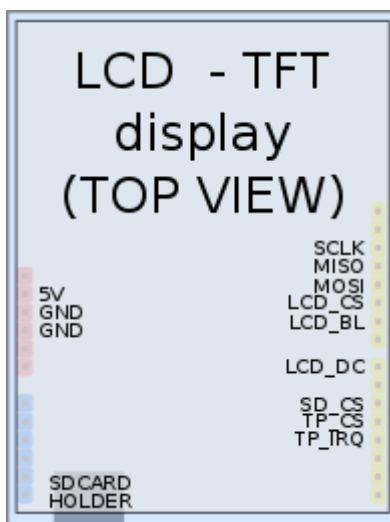


Figure 4. LCD TFT display with signals

2.4. Step-up headers and assembly

Step-up headers are required to connect the FRDM-MC-LVPMSM to the LCD TFT display because the board capacitors overlap at height. If the step-up headers are missing or not available, use compatible wires to connect the display to the rest of the system.

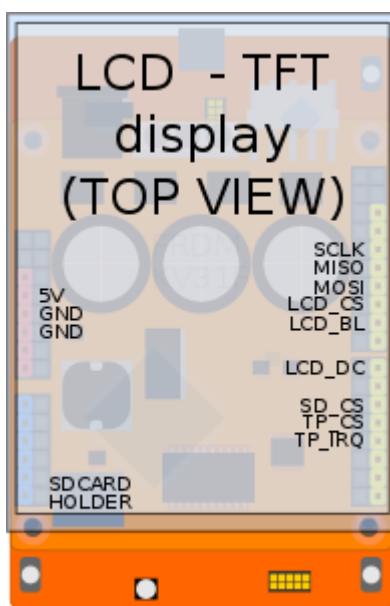


Figure 5. Assembled boards

3. Real-Time Operating System

The requirements and complexity of embedded applications are increasing, and this challenge forces programmers to use new methods to keep up with this increase. In a complex system where a number of tasks run in parallel and in real time, one way is to use a Real-Time Operating System (RTOS). It is scalable, easy to use, and has flexible options to expand the applications. FreeRTOS OS supports various platforms and MCU cores and is well-suited for the rising number of embedded applications. For support and additional information, see www.freertos.org.

FreeRTOS OS is able to handle the amount of tasks in embedded applications for all purposes. It is RAM- and ROM-friendly and has a small code footprint (depends on the configuration of the system). FreeRTOS OS includes:

- Preemptive or cooperative scheduler
- Trace functionality
- Stack overflow detection
- Support for various ARM cores
- Support for Memory Protection Unit (MPU)
- Support for binary semaphores or mutexes
- Support for queues and counting semaphores
- Software timers
- Memory schemes for memory management
- Low-power mode support

3.1. Tasks

Tasks are small programs which run independently of each other and have their own stack size, their own priority level, and can be created, destroyed, suspended, or be in the *running* state and handled. The main reasons for using tasks in a system are parallel code execution in time (where many tasks such as the graphical response of the display are handled), communication with remote devices, gathering values from internal or external sensors, or process computing under the internal inputs.

3.1.1. Task creation

Before handling the task, it is necessary to create and configure the task with proper parameters. In this application, four tasks are used and created with the *xTaskCreate* (...) function after all used peripherals are initialized. Every task has its own function according to system requirements. The tasks are:

- *SlowLoop_Task*
This task is used for motor speed control computation. It is described in [Section 6.1.2, “SlowLoop_Task”](#).
- *Freemaster_Task*
This task is used to handle the communication between the PC and MCU, which is invoked after the UART buffer receives data.

- *DemoMode_Task*
This task checks the press state of the SW2 on-board button which controls the demonstration mode of the motor spinning and turns it on or off.
- *Display_Task*
This task handles the graphical response of the application state to the TFT LCD display. This task runs in the infinite loop and is called every 25 Hz.

The tasks can be run either periodically or asynchronously, which may be invoked from the internal process or interrupt. The periodic tasks are executed with a periodic frequency, such as the *SlowLoop_Task*, *Display_Task*, and *DemoMode_Task*. Asynchronous or not, the periodically-executed task is invoked from an interrupt or from another task. *Freemaster_Task* is invoked from the *UART* interrupt and is selected as an asynchronous task.

3.1.2. Task handling

Only one task is running at a time, but the application contains several tasks which are inactive (in the *not running* state). The scheduler can turn one task to the *not running* (inactive) state and another to the *running* state. This is a fundamental functionality of an RTOS where several tasks are switched between two possible states (*running* or *not running*). Figure 6a shows a true task code execution, possible in multicore systems. The embedded device used has one core, so only one task can be executed at a time. Figure 6b shows a process where Task A is executed. At the end of Task A, the scheduler switches the execution code of Task B (*running* state). Task A is then switched to the *not running* state, and so on. All tasks have the same priority level and the same execution window time. The fast switching between all tasks is near to a parallel execution of code.

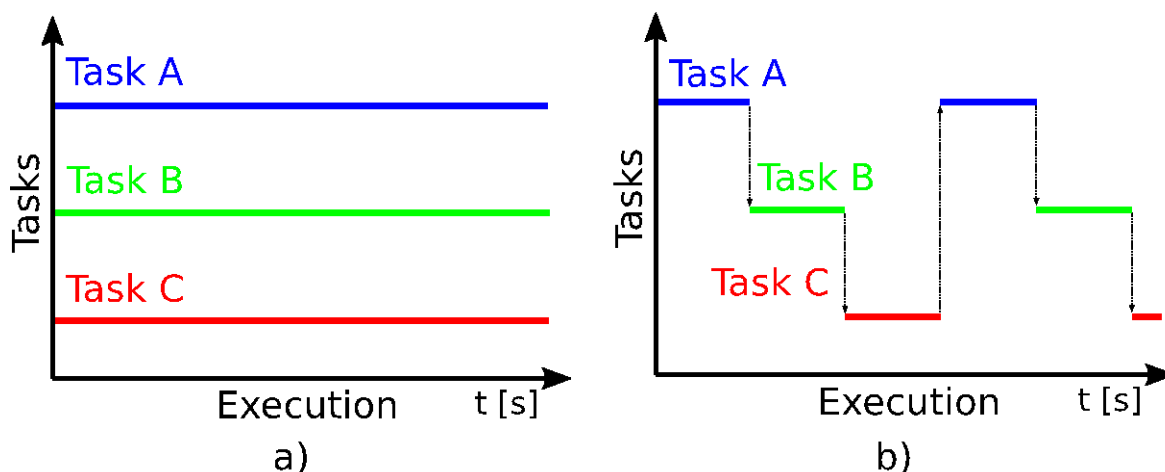


Figure 6. Code execution

Every task has a time slice to perform its action. At the end of a time slice, the scheduler is called and the next task that is ready to run is executed. The previous task is put to the *not running* state. For this purpose, a periodic interrupt provided by the hardware timer is used (such as *SysTick*). In this application, the time slice is defined as an interrupt frequency in *configTICK_RATE_HZ*, as 1000 Hz, or 1 ms. If the task requires more time to perform its action and another task is not required to run because it is not ready, the task is interrupted using *SysTick*. It can continue to operate until it is done or until a next interrupt occurs. The task frequency must be set to a lower value by the in-system delay function.

If there is no ready task waiting in the queue to be run, the IDLE task is created or hooked and switched by the scheduler.

3.1.3. Task scheduling

The task content can be switched at a maximum speed of the `configTICK_RATE_HZ` definition. Some applications may require a slower task switching than the defined maximum. A task delay function with the `vTaskDelay(value / (portTICK_PERIOD_MS))` parameter must be used for the time delay. A value is a time parameter defined in ms. This configuration provides a delay function. The task is called and executed in a defined frequency which depends on the parameter value, and is calculated from the core speed.

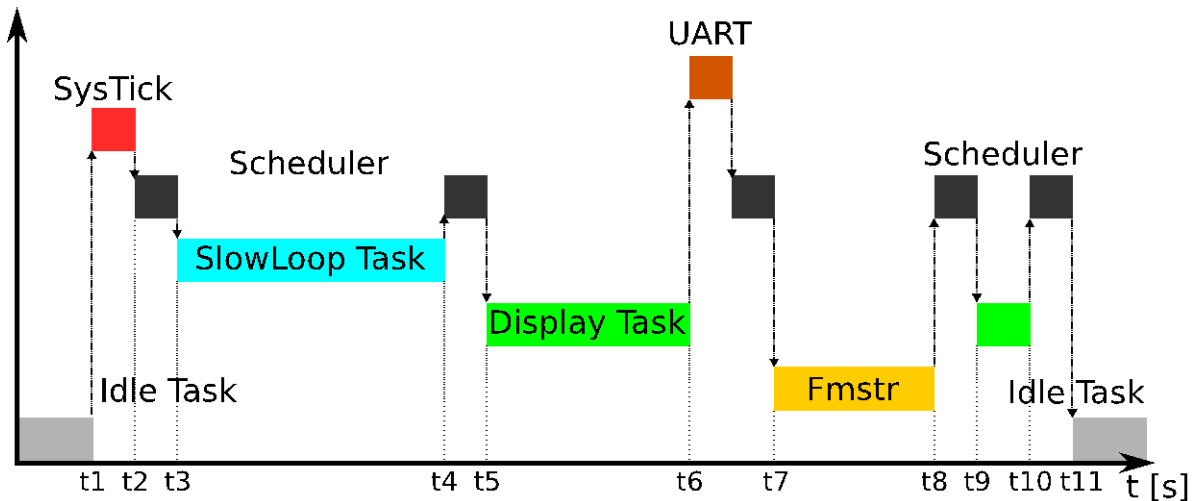


Figure 7. Code execution

The above figure shows a task execution example with the `SysTick` timer, UART periphery, and scheduler. There are four tasks. `SlowLoop_Task` has a priority value of 3 (the highest-priority task in the application), `Display_Task` has a value of 2, and so on. The time flow is as follows:

- At $t1$, `SysTick` occurred at the end of the defined time period, idle task is interrupted, the `SysTick` routine is performed and `Scheduler` is called at $t2$.
- `Scheduler` processes the inner routines, the first available task with the highest priority is selected and invoked, and `Scheduler` switches this *ready*, *not running* task to the *running* state.
- The highest-priority task is executed between $t3$ and $t4$.
- $t4$ is the time where the `SlowLoop_Task` process ends. It is the time where the next *ready* task must be executed. For this purpose, `Scheduler` is called and selects the first available task with the highest priority from the available tasks.
- The next task to be set to the *running* state is the `Display_Task`. The code execution starts at $t5$. The code is executed during the `UART` interrupt at $t6$. `Display_Task` execution stops and the `UART` interrupt is processed. `FreeMaster_Task` (`Fmstr`) is an asynchronous task intended for the communication process invoked from the `UART` interrupt with RTOS API functions `xSemaphoreGiveFromISR()` and `portYIELD_FROM_ISR()`.
- $t7$ processes the asynchronous `FreeMaster_Task` which is used for communication purposes. After this process, `Scheduler` is called (time $t8$).

- $t8$ and $t9$ define a time when *Scheduler* is processed. The next task is selected and preempted. *Display_Task* is resumed, set to the *running* state, and executed at time $t10$.
- *Scheduler* is processed, all available tasks in the queue are processed, and *Idle_Task* is created (or hooked) and processed at $t11$.

3.2. Interrupt processing

Figure 7 shows the process with the *UART* interrupt event which invokes *FreeMaster_Task*.

The interrupts may be as short as possible due to the system performance. The interrupts only handle the necessary communication data. Further data processing is done by *FreeMaster_Task*.

The RTOS system may use several possible mechanisms to handle external interrupts. One of the available methods to synchronize the interrupt with the task is the binary semaphore. The binary semaphore is used for synchronization between events. It can be used to unblock a task if an interrupt or event occurs. A task can be in a blocked state instead of being called periodically with the scheduler. When an interrupt occurs, the necessary data are processed in an interrupt and the process is deferred to a task. Two RTOS API functions are used: *xSemaphoreGiveFromISR()*, which “gives” a semaphore from the particular interrupt, and *xSemaphoreTake()*, which “takes” a semaphore. The *Scheduler* switch is forced using *portYIELD_FROM_ISR()*, its content switches from an interrupt to a task, the semaphore is taken, and the task re-enters the *blocked* state.

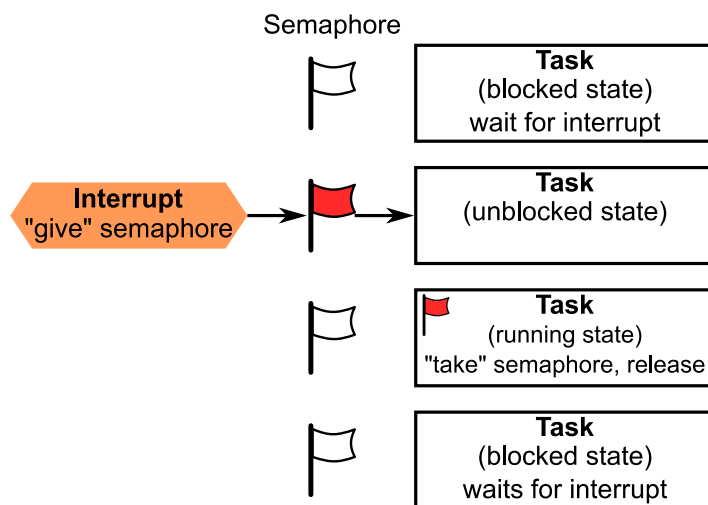


Figure 8. Semaphore flow

The above figure shows the process where the task is in the *blocked—not running* state until it is unblocked by a semaphore. An interrupt event occurs, the semaphore is given via a mechanism to a task which is then unblocked, the semaphore is “taken”, and the task runs. After that, the semaphore is released and the task is set to the *blocked* state, where it waits for a new event.

The RTOS API safe functions may be used in the *UART* interrupt if the priority is equal to or lower than *configLIBRARY_MAX_SYSCALL_INTERRUPT_PRIORITY*.

3.3. Memory management and stack

The RTOS can use four available RAM-allocation schemes prepared to handle a memory allocation. Every time a task, queue, or semaphore is created, a part of the RAM memory is required and consumed by the RTOS system. This space is *HEAP* and its size is defined as `configTOTAL_HEAP_SIZE`. When a task is created, the amount of memory consumed is `configMINIMAL_STACK_SIZE` or defined by the user. This memory is taken from the *HEAP* space, and also its size is specific for the application. The *HEAP* scheme is defined in the source code, where four possible implementations are available, but only one of them must be used.

The selected *HEAP* scheme 1 is suitable for most applications. It is the simplest scheme and allows for memory allocation (but not for memory freeing). The allocated memory can't be freed during the application operation. This memory scheme can be used if a task or queue is never deleted.

This scheme is:

- Deterministic
- Suitable for a system that never deletes tasks or queues

3.4. RTOS configuration

The RTOS configuration used in a particular application is shown in the following example and it can be also found in the *FreeRTOSConfig.h* source file.

Example 1. RTOS configuration

```
#ifndef FREERTOS_CONFIG_H
#define FREERTOS_CONFIG_H

#include "fsl_device_registers.h"

/*-----
 * Application specific definitions.
 *
 * These definitions should be adjusted for your particular hardware and
 * application requirements.
 *
 * THESE PARAMETERS ARE DESCRIBED WITHIN THE 'CONFIGURATION' SECTION OF THE
 * FreeRTOS API DOCUMENTATION AVAILABLE ON THE FreeRTOS.org WEB SITE.
 *
 * See http://www.freertos.org/a00110.html.
 *-----*/

/* Ensure stdint is only used by the compiler, and not the assembler. */
#define configUSE_PREEMPTION 1
#define configUSE_PORT_OPTIMISED_TASK_SELECTION 1
#define configUSE_IDLE_HOOK 1
#define configUSE_TICK_HOOK 0
#define configCPU_CLOCK_HZ ( DEFAULT_SYSTEM_CLOCK )
#define configTICK_RATE_HZ ( (TickType_t) 1000 )
#define configMAX_PRIORITIES ( 6 )
#define configMINIMAL_STACK_SIZE ( 256 )
#define configTOTAL_HEAP_SIZE ( ( size_t ) ( 8 * 1024 ) )
#define configMAX_TASK_NAME_LEN ( 5 )
#define configUSE_TRACE_FACILITY 1
```

```

#define configUSE_16_BIT_TICKS 0
#define configIDLE_SHOULD_YIELD 0
#define configUSE_MUTEXES 1
#define configQUEUE_REGISTRY_SIZE 8
#define configCHECK_FOR_STACK_OVERFLOW 2
#define configUSE_RECURSIVE_MUTEXES 0
#define configUSE_MALLOC_FAILED_HOOK 1
#define configUSE_APPLICATION_TASK_TAG 0
#define configUSE_COUNTING_SEMAPHORES 0
#define configUSE_QUEUE_SETS 0
#define configGENERATE_RUN_TIME_STATS 0
#define configSYSTICK_CLOCK_HZ ( configCPU_CLOCK_HZ )
#define configUSE_TICKLESS_IDLE 0

/* Co-routine definitions. */
#define configUSE_CO_ROUTINES 0
#define configMAX_CO_ROUTINE_PRIORITIES ( 2 )

/* Software timer definitions. */
#define configUSE_TIMERS 1
#define configTIMER_TASK_PRIORITY ( 2 )
#define configTIMER_QUEUE_LENGTH 10
#define configTIMER_TASK_STACK_DEPTH (128 )

/* Set the following definitions to 1 to include the API function, or zero
to exclude the API function. */
#define INCLUDE_vTaskPrioritySet 1
#define INCLUDE_uxTaskPriorityGet 1
#define INCLUDE_vTaskDelete 1
#define INCLUDE_vTaskCleanUpResources 1
#define INCLUDE_vTaskSuspend 1
#define INCLUDE_xTaskResumeFromISR 1
#define INCLUDE_vTaskDelayUntil 1
#define INCLUDE_vTaskDelay 1
#define INCLUDE_eTaskGetState 1
#define INCLUDE_xTimerPendFunctionCall 1
#define INCLUDE_xTaskGetIdleTaskHandle 1
#define INCLUDE_uxTaskGetStackHighWaterMark 1

/* Cortex-M specific definitions. */
#ifdef __NVIC_PRIO_BITS
    /* __BVIC_PRIO_BITS is specified when CMSIS is being used. */
    #define configPRIO_BITS __NVIC_PRIO_BITS
#else
    #define configPRIO_BITS 4 /* 15 priority levels */
#endif

/* The lowest interrupt priority that can be used in a call to a "set priority"
function. */
#define configLIBRARY_LOWEST_INTERRUPT_PRIORITY 15

/* The highest interrupt priority that can be used by any interrupt service
routine that makes calls to interrupt safe FreeRTOS API functions. DO NOT CALL
INTERRUPT SAFE FREERTOS API FUNCTIONS FROM ANY INTERRUPT THAT HAS A HIGHER
PRIORITY THAN THIS! (higher priorities are lower numeric values. */
#define configLIBRARY_MAX_SYSCALL_INTERRUPT_PRIORITY 5

/* Interrupt priorities used by the kernel port layer itself. These are generic

```

```

to all Cortex-M ports, and do not rely on any particular library functions. */
#define configKERNEL_INTERRUPT_PRIORITY          (
configLIBRARY_LOWEST_INTERRUPT_PRIORITY << (8 - configPRIO_BITS) )
/* !!!! configMAX_SYSCALL_INTERRUPT_PRIORITY must not be set to zero !!!!
See http://www.FreeRTOS.org/RTOS-Cortex-M3-M4.html. */
#define configMAX_SYSCALL_INTERRUPT_PRIORITY    ( configLIBRARY_MAX_SYSCALL_INTERRUPT_PRIORITY
<< (8 - configPRIO_BITS) )

/* Normal assert() semantics without relying on the provision of an assert.h
header file. */
#define configASSERT( x ) if( ( x ) == 0 ) { taskDISABLE_INTERRUPTS(); for( ;; ); }

/* Definitions that map the FreeRTOS port interrupt handlers to their CMSIS
standard names. */
#define vPortSVCHandler SVC_Handler
#define xPortPendSVHandler PendSV_Handler
#define xPortSysTickHandler SysTick_Handler

#endif /* FREERTOS_CONFIG_H */

```

4. Motor Control

The motor-control part is based on the Motor Control Reference Solution Package (MCRSP) software for a 3-phase Permanent Magnet Synchronous Motor (PMSM). The included motor-parameter identification algorithms can run on the 32-bit Kinetis V series MCUs. See *Sensorless PMSM Field-Oriented Control on Kinetis KV* (document [AN5237](#)) for more details about the configuration or driving of motors.

4.1. 3-phase PMSM

Sinusoidal PMSMs are popular due to good efficiency, low acoustic noise, and low torque ripple which is most efficient when driven by the Vector Control (VC) or Field-Oriented Control (FOC). The FOC technique brings overall improvements in drive (high efficiency, full torque control from zero to nominal motor speed, decoupled control of flux and torque, improved dynamics, and so on). For the PMSM control, it is necessary to know the exact rotor position. This application uses special algorithms to estimate the speed and position instead of using a physical position sensor.

4.2. Application concept

For a full torque control of a PMSM motor, know various parameters (such as the DC voltage and current values for each phase) to calculate the rotor position and speed. The other parameters that are required for full motor driving are phase inductance, resistance, rotor flux, number of poles, and more. They are measured using the Motor Control Application Tuning (MCAT) tool and described in *Motor Control Application Tuning (MCAT) Tool for 3-Phase PMSM* (document [AN4642](#)). A precise timing and value measurement is required because the maximal torque is achieved when the rotor magnetic flux and the stator magnetic flux are perpendicular to each other. The FOC is used for this purpose. The full driving principle is described in *Sensorless PMSM Field-Oriented Control* (document [DRM148](#)). The example is based on a framework model which uses two main loops for motor driving. The fast loop serves for value measurements (currents, voltages), fault protection, and calculation of the optimal

stator-rotor position. A precise timing is required, so the ADC interrupt must handle this. The speed loop handles the required speed.

4.3. Control theory

A 3-phase motor has a 3-phase winding connected to the FRDM-MC-LVPMSM shield. It also contains six power N-MOS transistors (two for each phase). The main principle is to create a 3-phase AC voltage on the motor windings. The PWM module of the KV31 MCU is used for this purpose. A correct switching of the six N-MOS transistors generates a 3-phase AC voltage that causes the rotation of the motor. The key is to have a precise measurement of the phase currents for FOC computing in a time where the measure does not affect the transient event. The current measurement is processed in the middle of the PWM duty cycle where the measurement may not be affected. The PWM reload generates a hardware trigger for the Programmable Delay Block (PDB) peripheral. The PDB generates the pre-triggers for the ADCs in the back-to-back mode delayed approximately $T_{\text{deadtime}}/2$ after the PWM reload. When the second (last) sample conversion is completed, the ADC generates an interrupt for the motor-control fast loop.

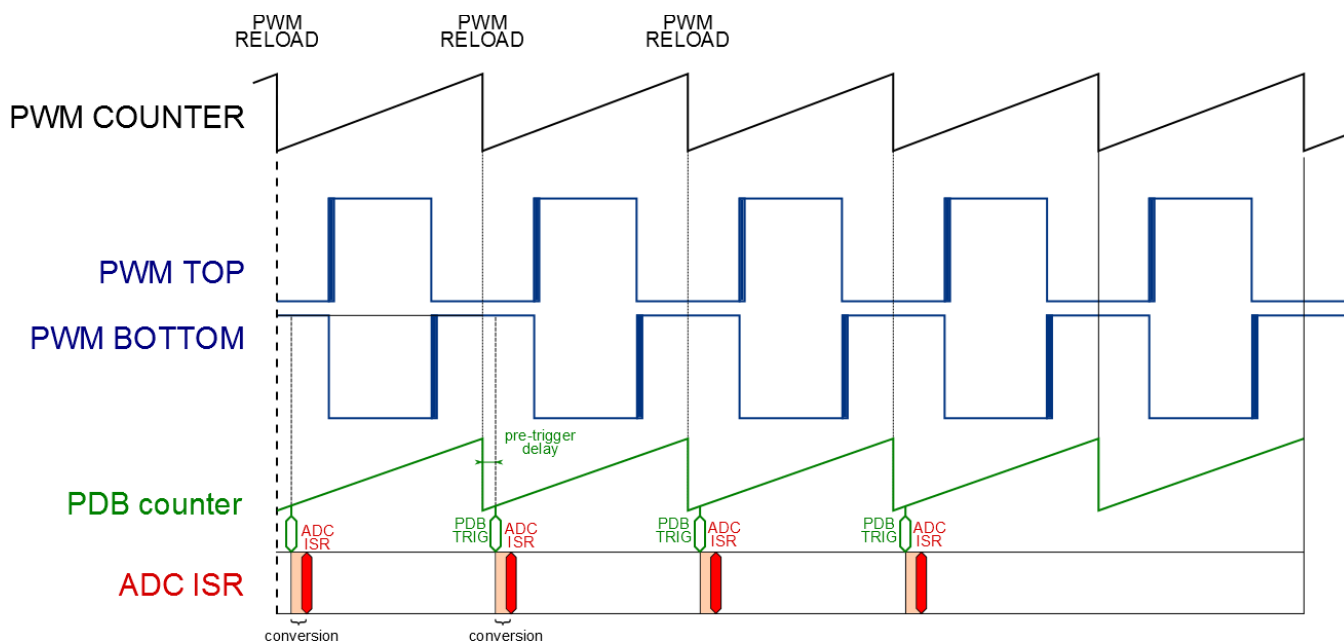


Figure 9. Code execution

The phase-current measurement and FOC computing are processed in the *ADC_ISR* handler (see Figure 9). This interrupt has the highest priority in the application due to phase measurement, fault checking, computing of rotor position, computing of space vectors, and updating the duty cycles of the PWM peripheral. The highest priority is needed for a precise application timing which is required in motor-control applications. The motor-control part is divided into two blocks. The first block is the important, non-breakable fast control loop which includes the described parts. The second block is the slow control loop which has a lower priority than the fast loop and is used to compute the speed of the motor (see the following figure).

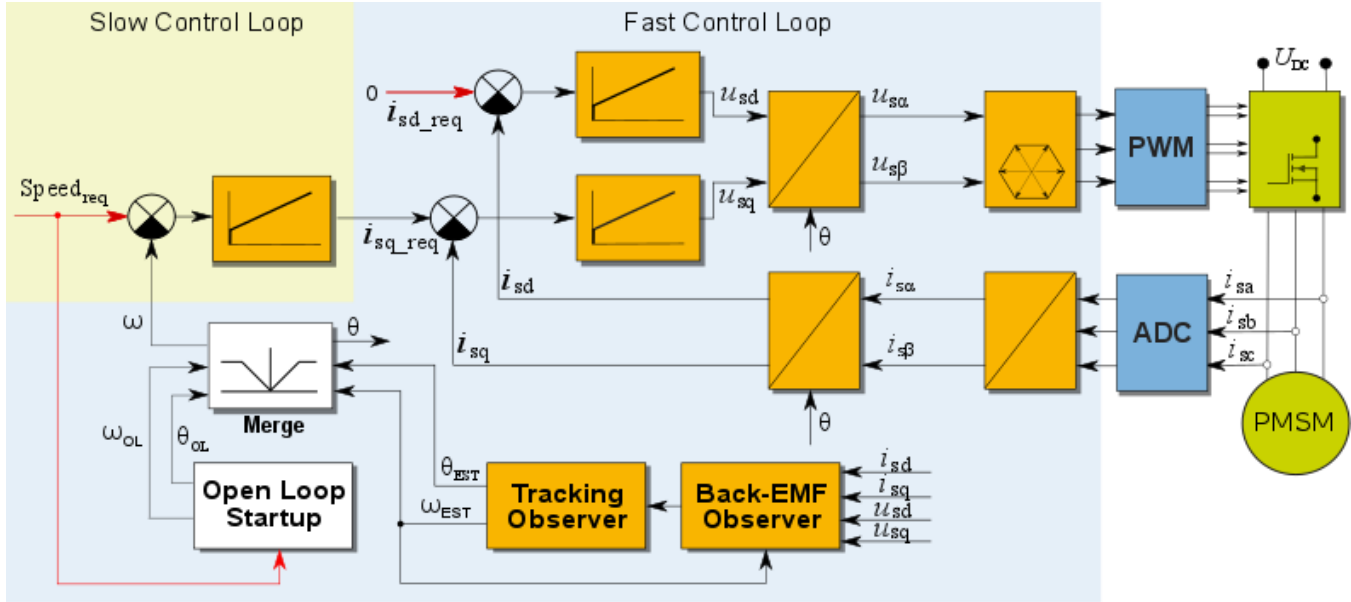


Figure 10. Code execution

The fast control loop is processed in the ADC interrupt with the highest priority and must not be preempted with other interrupts or events. The execution period is defined as the PWM frequency.

The slow control loop has lower priority than the fast control loop and can be preempted. The frequency of the operation typically ranges from 1 ms to 10 ms (depending on the system). This allows to move the slow control loop as a task in the RTOS system.

5. System Parts

The system uses two additional parts: eGUI graphical library and FreeMASTER debugging tool. Both of them have their respective application notes that describe their functions, implementations, and possibilities which can be useful for future system extension. The system concept is described in detail in the following sections.

5.1. Graphical library

The communication between the MCU board and the graphical display is done using a serial SPI periphery. It reduces the count of used pins to five plus a backlight-control pin for the background brightness. This configuration is suitable for a system where the display response is not very fast but requires a single external graphic driver to handle a 320x240 RGB display. The used display shield has the HX8347 graphical driver which enables full display control and has an amount of internal settings to be configured before using the display.

5.1.1. eGUI

The display is driven by eGUI software (an object-based open-source graphical framework suitable to drive graphical displays). eGUI supports several graphical ICs and touch-screen and communication peripherals, such as SPI (used) and SD card. eGUI can draw various objects such as gauges, textboxes,

labels, bitmap images, and other. eGUI can also draw simple objects such as lines, boxes, circles, and other. It is targeted for devices with a small RAM footprint. All necessary code is stored in the MCU's flash and its size is based on the objects used.

eGUI uses a standard file structure and functions described in *Freescale Embedded GUI (D4D)* (document [DRM116](#)) which contains additional information about functions, parameters, graphical objects, and more.

5.1.2. Graphical components

The graphical objects used are defined in the eGUI source code. Several objects must be drawn on the display according to the definitions in the configuration files which are described below. The files that define the behavior of the application are located in the *src/D4Di/common_source* folder:

- *d4d_screen_entry.c*—graphical object declaration
- *d4d_user_cfg_app.h*—driver user configuration file
- *d4d_user_cfg.h*—user configuration file (for example, to define the LCD driver and communication plugin used)
- *d4dlcdhw_kinetis_spi_cfg.h*—SPI configuration
- *fonts.c*—font data
- *picture.c*—background and gauge image data

Selecting the low-level drivers required for communication, the hardware communication profile is defined in the *src/D4D/low_level_drivers/* folder:

- The *lcd_controllers_drivers/hx8347/** folder contains low-level routines for handling LCD displays.
- The *lcd_hw_interface/kinetis_spi_bm/** folder contains routines for SPI initialization functions compatible with the eGUI framework.

5.1.3. Screen draw

All objects to be drawn on the LCD display are defined in the *d4d_screen_entry.c* source file. The used driver and the communication peripherals are defined in the *d4d_user_cfg.h* file. After the objects and functions are properly defined, the display initialization routine *D4D_Init(&screen_entry)* is called with the *screen_entry* parameter. This routine initializes the SPI communication driver and routines for communication with the graphical driver, performs a screen initialization, and the screen objects are then drawn on the display.

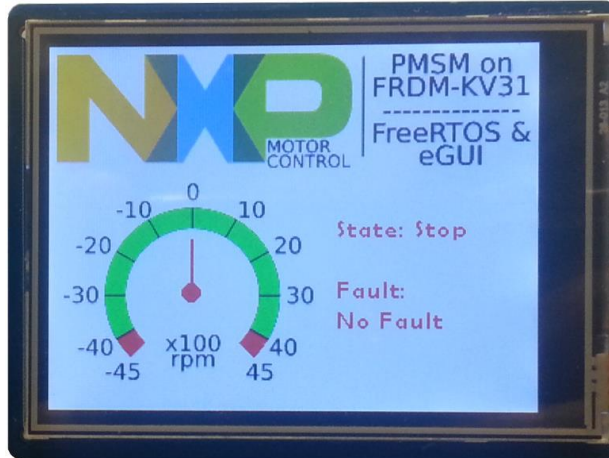


Figure 11. Drawn display

During the embedded system operation, some values change their content (such as speed, current voltage, or application state variables) and these changes are drawn on the display. The dynamic objects such as texts, labels, progress bar, and gauges must be set with the new variable values and it is necessary to redraw the display with these new changes. The eGUI implement function *D4D_Poll()* redraws the display with the actual set of objects. This function is used in *Display_task*.

5.2. FreeMASTER

FreeMASTER is a computer and embedded system on-line debugging tool used for efficient on-board system debugging. It enables you to see and modify in-system parameters (variables), plots various graphs during the application operation, and shows the variables with a content change or static variables. It can be also used to configure the system during operation and to configure the motor-control part. FreeMASTER installation and configuration with the PMSM motor control is described in section 7.2 of *PMSM Control Reference Solution Package* (document [PMSMCRSPUG](#)).

FreeMASTER configuration is set to be interrupt-driven as *short interrupt* and uses the UART0 peripheral. The *freemaster_cfg.h* configuration file is configured to work properly with this example. The important definitions are:

```
#define FMSTR_SHORT_INTR      1      /* SCI FIFO-queuing done in interrupt */
#define FMSTR_SCI_BASE       FMSTR_UART_PORT /* Defined in main.h */
#define FMSTR_SCI_INTERRUPT  FMSTR_UART_VECTOR /* Defined in main.h */
#define FMSTR_USE_SCI        1      /* To select SCI communication interface */
```

6. FreeRTOS and Motor Control Implementation

This section describes the incorporation of the RTOS and the motor-control framework (MCRSP) into one working system. Both of them must comply with specific settings' conditions such as interrupt priorities and peripheral setup. The motor-control framework contains two control loops: the slow control loop and the fast control loop. The fast control loop is a system-critical, real-time process because precise timing, measurement, fault checking, and motor control is required to be handled as the highest priority and must not be interrupted with other tasks or events.

The slow control loop is not necessarily a system-critical process that must be incorruptible and it must be managed as an RTOS process. The implementation of both systems into an embedded system is shown in this figure:

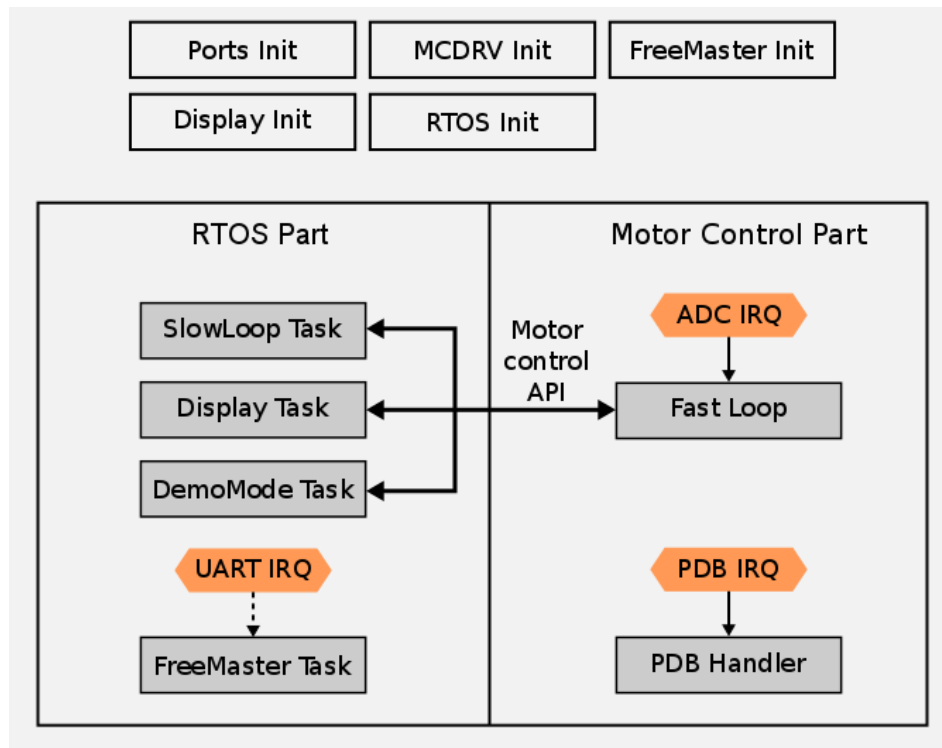


Figure 12. Embedded system

6.1. Program flow

The program flow is very important in embedded software designs. It is a process where the functions and system components are initialized and the other parts of the system are processed. Right after a device reset, the internal core and memory components are initialized, the clock configuration is set, and the main routine is started. The following sections show the program flow for the main function, four tasks, and the motor-control part.

6.1.1. Main initialization

The main routine-initialization functions are performed after any device reset, called only once, and they never reach the endless *for* loop. The task management is handled by the RTOS system and the system interrupts are handled on their own. The scheduler starts after the initialization of internal registers, clocks, and other modules is completed. The following figure shows the main routine flowchart after the MCU reset.

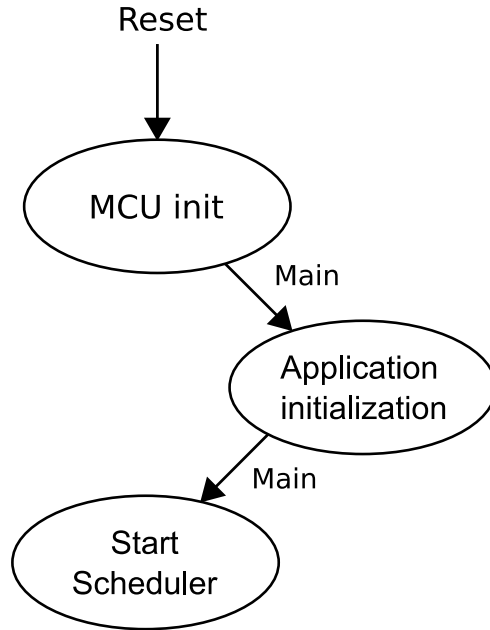


Figure 13. Main routine flow

6.1.2. SlowLoop_Task

SlowLoop_Task is a task which processes the speed-control loop of the driven motor. *SlowLoop_Task* is implemented as a task handled by the RTOS system because the time resolution is set to 1 ms, which is a sufficient period for the motor dynamic control. *SlowLoop_Task* uses the *SM_StateMachineSlow()* function (it is a part of the motor-control algorithms solution). This task is called periodically at a maximum possible frequency defined with the highest priority level. The *SlowLoop_Task* flowchart is shown in this figure:

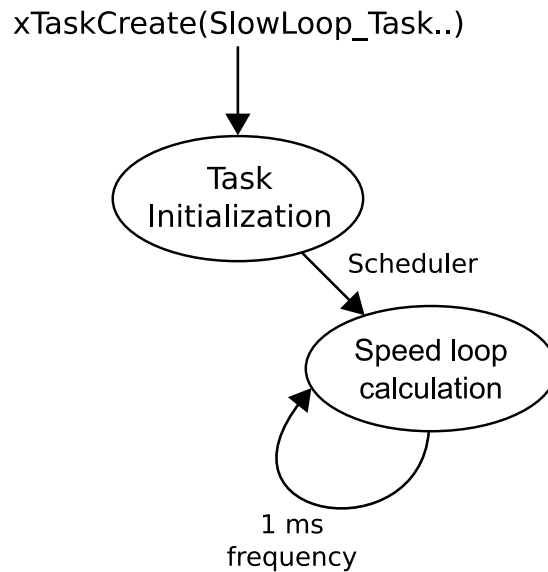


Figure 14. SlowLoop_Task flowchart

6.1.3. DemoMode_Task

DemoMode_Task handles the demo mode operation which demonstrates the motor spinning from the predefined speed values in both motor directions. This task is called periodically with a period of 100 ms. At every task execution, the state of the SW2 push-button is checked. When this button is pressed, the internal bool variable is set and the motor is enabled to spin. The next pressing of the button stops the motor operation. The explicit task flowchart is shown in Figure 15b. The simplified flowchart is shown in Figure 15a.

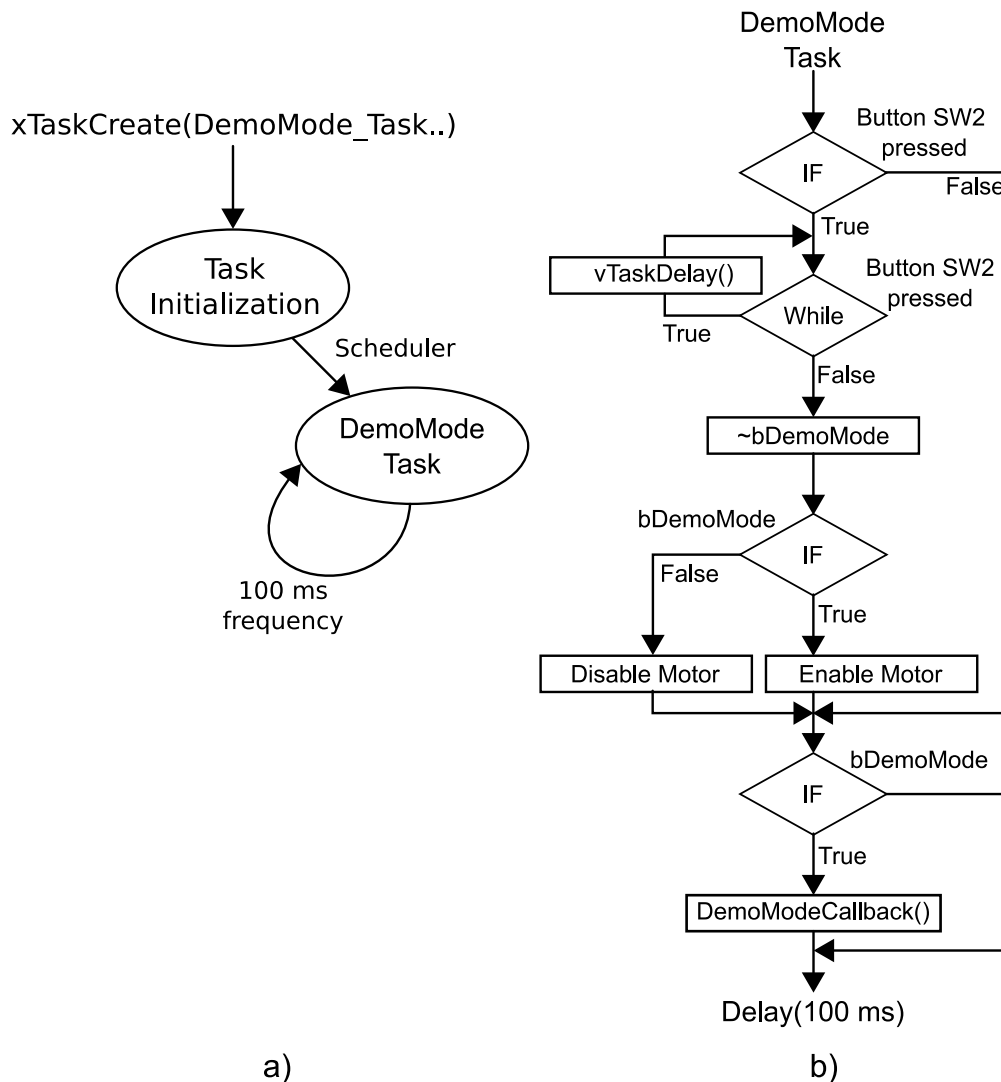


Figure 15. *DemoMode_Task* flowchart

6.1.4. Display_Task

The mounted LCD display shows various user-defined content, such as motor speed, applications states, and faults (if any). An object can be drawn either statically or dynamically. The statically drawn object is a label whose text is not updated in the process or a background image. It is drawn only once at the initialization. Dynamic objects (such as gauges or label texts) change their values during the operation.

The dynamic objects are redrawn dynamically with *Display_Task* at a frequency of 25 ms, which is a sufficient period for a smooth display refreshing. For a better performance, the gauge that shows the actual motor speed is refreshed at every task execution (25 ms), while the application and fault statuses are refreshed only after their values change. The high-level task flowchart is shown in [Figure 16a](#) and the detailed flowchart is shown in [Figure 16b](#).

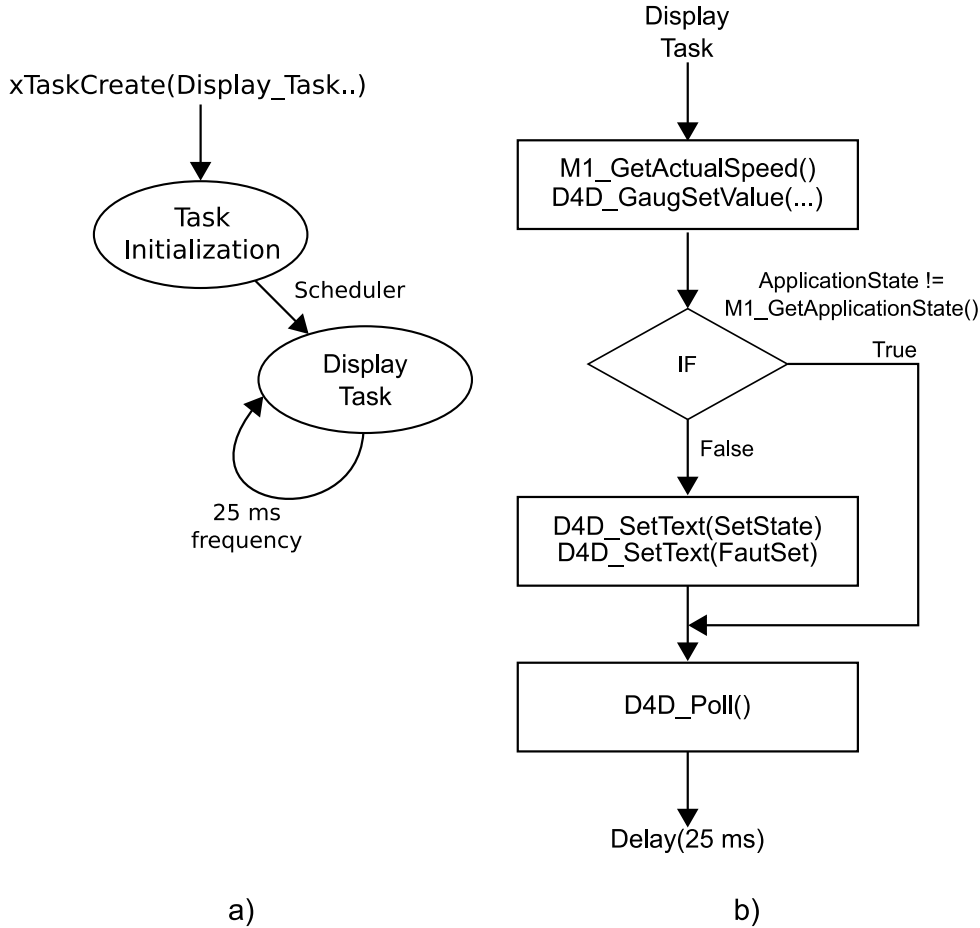


Figure 16. *Display_Task* flowchart

6.1.5. FreeMaster_Task

FreeMaster_Task has the second lowest task priority above the IDLE process. It is not executed periodically (as the other tasks), but it is invoked from the UART interrupt. The task is performed only after the communication data are received from the FreeMASTER computer side. The task is blocked by a semaphore during the remaining time. The task is unblocked by the semaphore mechanism after the data are received by the internal FIFO register of the UART periphery (while the interrupts are enabled). The UART handler occurs, the *FMSTR_Isr()* function is called, and the data from the UART FIFO register are stored in the internal FreeMASTER structure. The full communication process is performed in the task which must be unblocked by the *xSemaphoreGiveFromISR()* function and the content is switched to a proper task. [Figure 17a](#) shows the task and semaphore initialization. [Figure 17b](#) shows the casual process flow.

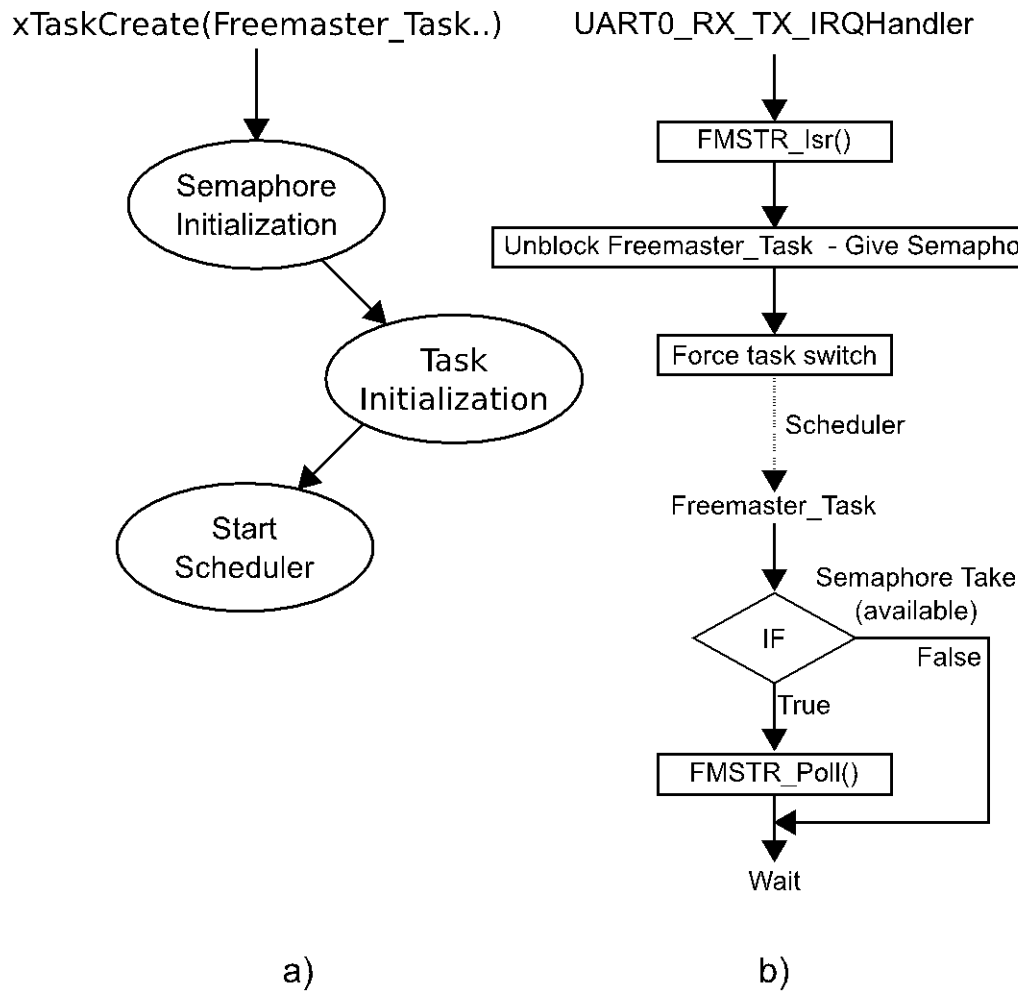


Figure 17. FreeMaster_Task flowchart

6.1.6. Fast loop process—ADC interrupt

Fast loops are processed outside of the RTOS system and they are not affected by other interrupts. The execution period is defined as a macro for the FlexTimer peripheral and is set to 100 μ s (10 kHz). This task processes the measurement, calculations, and functions for the fault detections.

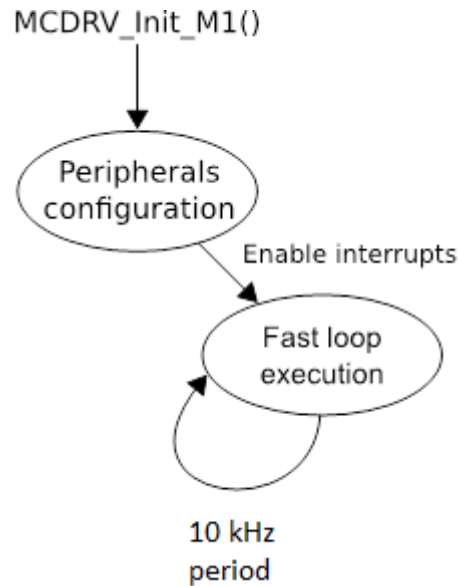


Figure 18. Fast loop flowchart

6.1.7. Programmable Delay Block (PDB)

This interrupt has the second highest priority after the ADC module. Is not directly used to handle any of the operations, but it is required when an error occurs in the ADC module measurement process.

6.2. Interrupt configuration

Interrupts are an integral part of modern real-time embedded systems and can respond to internal or external events and handle them. Interrupts are used in real-time systems where precise timing is critical (for example current measurement). The KV31 MCU's core is ARM Cortex CM4F with lots of possibilities in the interrupt settings. By default, the ARM core supports up to 255 interrupt priorities and 8 bits in the register. The manufacturer can also implement a lower value of available interrupts' levels. The KV31F MCU supports 4 bits of interrupts or 16 values (from 0 to 15).

Correct interrupt settings are important for a good concurrent running of two parts. The RTOS system uses the interrupt-driven *SysTick* timer to handle tasks, while the motor-control part calls the fast-loop interrupt. The motor-control fast loop has higher priority than the RTOS system and must have the highest priority in the whole system. Don't get confused by the task priorities, they have their own set of priorities defined in the RTOS system.

This provides the possibility to set correct interrupts for the whole system, sorted from the highest priorities to the lowest priorities:

- Motor-control fast loop—highest priority
- Programmable Delay Block (PDB)
- RTOS system call
- UART periphery
- RTOS kernel—lowest priority

A set of priorities for the used peripherals or system implementations must be configured via the CMSIS macro `NVIC_SetPriority(IRQn, priority)` and enabled by `NVIC_EnableIRQ(IRQn)`. All peripherals that have the ability to interrupt have a value of 0—highest default priority. The peripherals must be configured to work properly. The following figure shows the defined priority levels in an application where the RTOS system has a priority level of 5 and below. The motor-control part has a priority level of 4 and above and it is not affected by the RTOS system which results in an improved response and a precise timing of the motor-control application part.

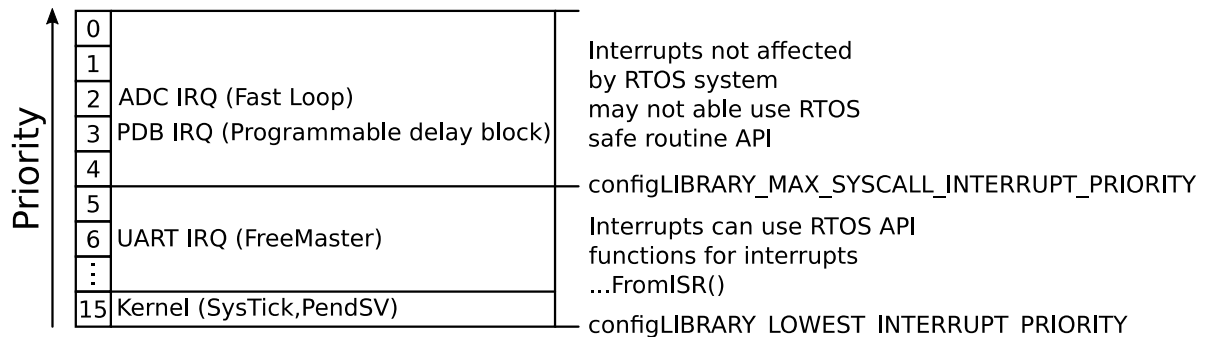


Figure 19. Code execution

The `FreeRTOSConfig.h` file defines the maximum and minimum priority levels for the RTOS. The interrupts below this value can use the RTOS interrupt safe routines. The interrupt safe function higher than this value must not be used.

```
#define configLIBRARY_MAX_SYSCALL_INTERRUPT_PRIORITY (5)
```

The kernel interrupt priority is set as:

```
#define configLIBRARY_LOWEST_INTERRUPT_PRIORITY (15)
```

The motor-control interrupt definition based on the `FreeRTOSConfig.h` definitions is:

```
NVIC_EnableIRQ(ADC1_IRQn); /* Enable Interrupt */
NVIC_SetPriority(ADC1_IRQn, configLIBRARY_MAX_SYSCALL_INTERRUPT_PRIORITY - 3);
```

```
NVIC_EnableIRQ(PDB0_IRQn); /* Enable Interrupt */
NVIC_SetPriority(PDB0_IRQn, configLIBRARY_MAX_SYSCALL_INTERRUPT_PRIORITY - 2);
```

This definition allows for the critical motor-control part to be unaffected by the RTOS system. The RTOS scheduler latency is not critical so the other parts (such as speed control loop or communication) can be managed by the system. The code execution time line is shown in the following figure.

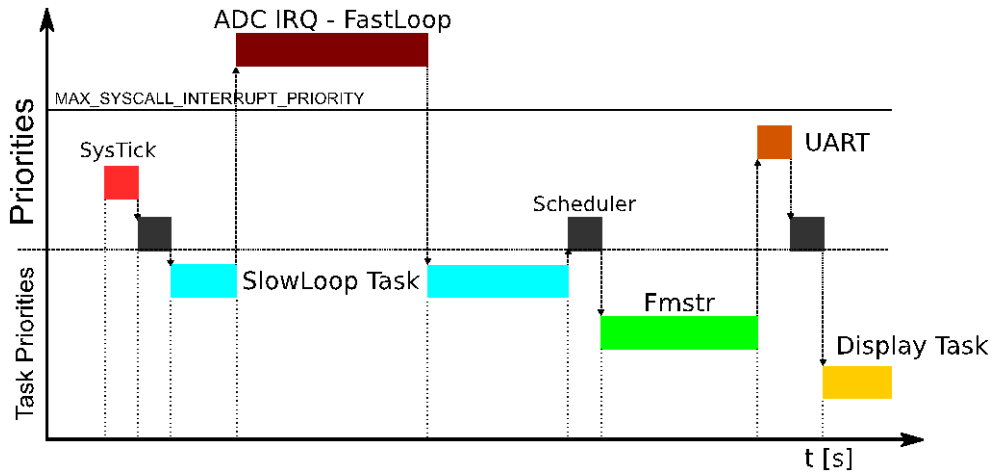


Figure 20. Code execution

6.3. CPU load and memory usage

The following information is valid for the whole application built in the KDS IDE with the optimization parameter set for the code size (“-Os”). The following table shows the memory usage. It is calculated by the arm-none-eabi-size program from the *.elf file. It includes a 2-KB FreeMASTER recorder buffer (allocated in the RAM), the motor-control part, eGUI, and FreeRTOS with HEAP in the RAM.

Table 1. KV31 memory usage

—	MKV31F
Flash usage [B]	56524
RAM usage [B]	11124

The approximate CPU load is measured separately for the motor-control part and for the FreeRTOS kernel. The CPU load depends on the fast control loop (FOC calculations) and RTOS operations in a specific time. The result is only approximate.

Table 2. KV31 CPU load

—	MKV31F
Motor-control part	29,5 %
RTOS kernel	5 %

7. Conclusion

This application note describes the implementation of a sensorless FOC for 3-phase PMSM motors on NXP 32-bit Kinetis V MCU with FreeRTOS, eGUI, and a description of important parts and configurations. The eGUI graphical library is also used to draw application states and speed gauges on the connected LCD. The FreeRTOS capability enables handling several tasks together with the critical real-time application.

8. Acronyms and Abbreviations

Table 3. Acronyms and abbreviations

Term	Meaning
AC	Alternating Current
ADC	Analog-to-Digital Converter
AN	Application Note
CPU	Central Processing Unit
DRM	Design Reference Manual
FOC	Field-Oriented Control
FTM	FlexTimer Module
I/O	Input/Output interfaces between a computer system and the external world—a CPU reads an input to sense the level of an external signal and writes to an output to change the level of an external signal.
LCD	Liquid Crystal Display
MCAT	Motor Control Application Tuning tool
MCRSP	Motor Control Reference Solution Package
MCU	Microcontroller
PDB	Programmable Delay Block
PMSM	Permanent Magnet Synchronous Machine
PWM	Pulse-Width Modulation
RAM	Random Access Memory
RTOS	Real-Time Operating System
TFT	Thin-Film Transistor
UART	Universal Asynchronous Receiver/Transmitter

9. References

These references are available on www.nxp.com:

1. *Sensorless PMSM Field-Oriented Control* (document [DRM148](#))
2. *KV31F Sub-Family Reference Manual* (document [KV31P100M120SF7RM](#))
3. *Sensorless PMSM Field-Oriented Control on Kinetis KV* (document [AN5237](#))
4. *Motor Control Application Tuning (MCAT) Tool for 3-Phase PMSM* (document [AN4642](#))
5. FreeRTOS – online documentation at www.freertos.org

10. Revision History

Table 4. Revision history

Revision number	Date	Substantive changes
0	08/2016	Initial release.

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