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Numerical Static Analysis of Interrupt-Driven Programs via Sequentialization

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ABSTRACT
Embedded software often involves intensive numerical computations and thus can contain a number of numerical run-time errors. The technique of numerical static analysis is of practical importance for checking the correctness of embedded software. However, most of the existing approaches of numerical static analysis consider sequential programs, while interrupts are a commonly used technique that introduces concurrency in embedded systems. To this end, a numerical static analysis approach is desired for embedded software with interrupts. In this paper, we propose a sound numerical static analysis approach specifically for interrupt-driven programs based on sequentialization techniques. A key benefit of using sequentialization is the ability to leverage the power of the state-of-the-art analysis and verification techniques for sequential programs to analyze interrupt-driven programs. To be more clear, we first propose a sequentialization algorithm to sequentialize interrupt-driven programs into non-deterministic sequential programs according to the semantics of interrupts. On this basis, we leverage the power of numerical abstract interpretation to analyze numerical properties of the sequentialized programs. Moreover, to improve the analysis precision, we design specific abstract domains to analyze sequentialized interrupt-driven programs by considering their specific features. Finally, we present encouraging experimental results obtained by our prototype implementation.

Categories and Subject Descriptors
D.2.4 [Software Engineering]: Program Verification; F.3.1 [Logics and Meanings of Programs]: Specifying and Verifying and Reasoning about Programs

Keywords
Embedded Software, Interrupt-Driven Programs, Static Analysis, Abstract Interpretation, Sequentialization

1. INTRODUCTION
An interrupt is a signal to the processor indicating an event that needs immediate attention and requiring the interruption of the current code the processor is executing. Interrupts are commonly used in embedded systems to introduce concurrency, which is required for real-time applications. For example, embedded control software often uses interrupts to obtain sensor data from the physical environment. In a program, during the running of the normal tasks, an interrupt service routine (ISR) is invoked once an interrupt alerts the processor to a higher-priority condition. Such a program is said to be interrupt-driven. In interrupt-driven programs (IDP), interrupts may cause unexpected interleaving executions and even unexpected erroneous behaviors. Therefore, there is a great need in practice to ensure that IDPs work correct in the presence of interrupts, since IDPs are often used in safety critical fields such as avionics, spaceflight and automotive. However, analyzing and verifying IDPs are challenging. The main reason is that an ISR may be triggered at any time and the number of possible execution interleavings caused by concurrency between tasks and ISRs is quite huge.

IDPs often appear in embedded systems, while embedded software usually involves intensive numerical computations which have the potential to cause numerical runtime errors (such as division by zero, arithmetic overflow, and array out-of-bound) [2]. Hence, analyzing numerical properties of IDPs is of significant importance to check for the correctness of embedded software. Numerical static analysis is a commonly used technique to discover numerical properties of programs. However, most of the existing numerical static analysis approaches consider only sequential programs. For IDPs, if we perform numerical static analysis over each task and each ISR separately without considering the interleaving between them, the analysis results may be not sound.

```
1: int x, y, z;
2: void task()
3: { if(x < y)
4: { z = 1/(x - y);
5: } }
6: return;
7: }

1: void ISR()
2: { x++; y--; }
3: return;
4: }
```

Figure 1: A motivating example

Fig. 1 shows a motivating example, where the functions task() and ISR() represent the entry functions of a task and an interrupt service routine respectively. task() performs
the division operation only when \( x \) is strictly less than \( y \).

\( \text{ISR}(\cdot) \) increases \( x \) by 1 and decreases \( y \) by 1. Performing
numerical static analysis over \( \text{task}(\cdot) \) without considering in-
terrupts would answer that the program is safe. However, when
taking interrupts into consideration, the \( \text{task}(\cdot) \) func-
tion is not safe. For example, if \( x = 1, y = 3 \) and the in-
terrupt fires between line 3 and 4 of \( \text{task}(\cdot) \), there will be
a division-by-zero error in this program. Thereby, a sound
numerical static analysis method is desired for IDPs.

Recently, a few numerical static analysis approaches have
been proposed for general concurrent programs such as multi-
threaded programs [15, 16], but very few approaches have
considered the specific features of IDPs [6, 17]. Compared
with multi-threaded programs, IDPs have their own specific
features. For example, higher-priority interrupts will never
be interrupted by lower ones. In other words, tasks and
lower priority interrupts will never be aware of the intermedi-
ate states of higher priority interrupts during their running.
Moreover, IDPs in embedded systems usually make use of
hardware features such as interrupt mask registers (IMR) to
control the interference between tasks and interrupts.

In this paper, we propose a sound numerical static analysis
approach specifically for IDPs. The main idea is as follows.
We first sequentialize IDPs into non-deterministic sequen-
tial programs according to the semantics of interrupts and
the interaction between tasks and interrupts. Sequentializa-
tion then enables the use of existing analysis and verification
techniques for sequential programs to verify IDPs. After
that we make use of numerical abstract interpretation to
analyze the numerical properties of the sequentialized IDPs.
Moreover, by considering the specific features of sequential-
lized interrupt-driven programs, we design specific abstract
domains to improve the precision of numerical static anal-
ysis. The preliminary results show that our approach is
promising.

The rest of this paper is organized as follows. Section 2
presents the program syntax of IDPs. Section 3 presents
methods for sequentializing IDPs. In Section 4, we show how
to use abstract interpretation to analyze the sequentialized
IDPs. Section 5 presents our implementation together with
preliminary experimental results. Section 6 discusses some
related work. Finally, conclusions as well as suggestions for
future work are given in Section 7.

2. INTERRUPT-DRIVEN PROGRAMS

An IDP consists of a fixed set of a finite number of tasks
and interrupts, each of which has an entry function. In this
paper, recursive functions are not allowed in IDPs, and all
functions have been inlined (except the entry functions of
tasks and interrupts). Tasks are scheduled in a cooperative,
round-robin manner and interrupts are assigned priorities.
Moreover, the tasks execute with interleaved semantics (on
a uniprocessor) and each task can finish its job within the
given time slice. Each interrupt has a fixed priority level
attribute \( p \) which is a positive integer and a larger priority
level means higher priority. In other words, higher-priority
interrupts can interrupt lower-priority interrupts and tasks,
but the opposite preemption can not happen. For the sake of
presentation, we use the following two assumptions through-
out this paper:

1) We assume that an IDP only consists of a single task.

Since tasks are scheduled in a cooperative, round-robin
manner, for an IDP including multiple tasks, we can
design a wrapper function which consists of calling
each of the tasks one by one in sequence to simulate
the round-robin scheduling of multi-tasks.

2) We assume that each priority level contains only one
interrupt. For an IDP which contains multiple inter-
rupts with the same priority, we can design a new
wrapper ISR of that priority to over-approximate
the program behaviors. The new wrapper ISR consists of
a loop in which each iteration non-deterministically calls
one of the original interrupts of that priority.

\[
\begin{align*}
\text{Expr} & \quad : = \quad l \quad | \quad C \quad | \quad E_1 \circ E_2 \quad \text{where} \quad l \in \{\mathit{NV}\} , C \quad \text{is a constant}, \quad E_1, E_2 \in \text{Expr} \quad \text{and} \quad \circ \in \{\{+, -, \times, \div\}\} \\
\text{Stmt} & \quad : = \quad l \quad \mid \quad g \quad = \quad l \quad \mid \quad e \quad = \quad c \quad \mid \quad S_1 \mid S_2 \mid \text{skip} \mid \text{enableISR}(i) \mid \text{disableISR}(i) \mid \text{if} \ e \ \text{then} \ S_1 \ \text{else} \ S_2 \\
& \quad \mid \quad \text{while} \ e \ \text{do} \ S \\
& \quad \text{where} \quad l \in \{\mathit{NV}\} , g \in \{\mathit{SV}\} , e \in \{\mathit{Expr}\} , i \in \{1, N\} , \ S_1, S_2, S \in \text{Stmt} \\
\text{Task} & \quad : = \quad \text{entry} \ (\text{where} \ \text{entry} \in \text{Stmt}) \\
\text{ISR} & \quad : = \quad \{\text{entry}, p\} \ (\text{where} \ \text{entry} \in \text{Stmt}, \ p \in \{1, N\}) \\
\text{Prog} & \quad : = \quad \text{Task} \ \parallel \ \text{ISR}_1 \ \parallel \ \ldots \ \parallel \ \text{ISR}_N
\end{align*}
\]

Figure 2: Syntax of interrupt-driven programs

We now present a simple language to model IDPs. The
syntax of our language is depicted in Fig. 2. An IDP consists
of one task and \( N \) interrupts. \( \text{ISR} := \{\text{entry}, p\} \) represents
the ISR entry function of an interrupt and its priority. With-
out loss of generality, we assume that the priority \( p \) is equal
to the index of the corresponding interrupt and use \( \text{ISR}_i \)
to represent the interrupt with priority \( p = i \) where \( i \in \{1, N\} \).
\( \text{enableISR}(i) \) and \( \text{disableISR}(i) \) represent respectively
the instructions that enable and disable an interrupt by writ-
ting to the interrupt mask register (IMR). We use \( SV \) and
\( NV \) respectively represent the set of shared and non-shared
variables.

For the sake of simplicity but without loss of generality,
we restrict that shared variables can only appear in the fol-
lowing two kinds of statements:

- \( l = g \) which represents reading the value from a shared
  variable \( g \) to a non-shared variable \( l \).
- \( g = l \) which represents writing the value of a non-
  shared variable \( l \) to a shared variable \( g \).

In fact, any program statement involving shared variables
can be transformed into this form by introducing auxiliary
variables. Moreover, we assume that the statements \( g = l \)
and \( l = g \) are atomic.

In this paper, we consider analyzing IDPs in the level of
source code rather than machine code, and one program
statement in the source code can be translated into several
machine instructions. Hence, an interrupt may happen dur-
ing the running of a program statement if the statement is
not atomic. For example, consider an IDP that contains
one task \( \{z = x + y;\} \) and one interrupt whose ISR is
\( \{x = 1; y = 1;\} \). Suppose that both shared variables \( x, y \)
are initialized to 0. If we consider only the case that the
interrupt happens before or after the assignment statement
\( \{z = x + y;\} \) in the task, the value of variable \( z \) can be 0 or
2. However, the interrupt may happen during the running
of this statement at machine instruction level. For example,
the interrupt may happen after reading \( x \) and before reading
3. SEQUENTIALIZING INTERRUPT-DRIVEN PROGRAMS

In this section, we will describe how to sequentialize IDPs into non-deterministic sequential programs in a sound way. In other words, we will guarantee that the program behaviors of the sequentialized program are an over-approximation of the behaviors of the original IDP. In the following, we will first show in Sect. 3.1 how to sequentialize IDPs into sequential programs by considering IDPs as priority preemptive scheduling systems. Then we will make use of data flow dependency information between tasks and interrupts to remove unnecessary scheduling in Sect. 3.2. After that, we will consider further the IMR information at program point to remove unnecessary scheduling in Sect. 3.3.

3.1 Sequentializing IDPs by simulating priority preemptive scheduling

First, let us review the running process of an IDP. During the running of a task, the i-th interrupt may be fired before any program statement of the task. If the i-th interrupt is fired, the task is preempted and resumes only when ISR has finished. Hence, this situation can be simulated by calling the ISR function in the stack once the i-th interrupt is fired. Similarly, before each program statement of the i-th interrupt, if the j-th interrupt with higher priority (i.e., satisfying i < j) is fired, ISR is preempted and resumes only when ISR has finished. This situation also can be simulated by calling the ISR function in the stack when the j-th interrupt is fired. In general, because the ISR of a preempted lower-priority interrupt (or task) will not resume until the ISR of a higher-priority interrupt has finished, the task and ISRs in an IDP can share the same stack. In other words, in IDPs, interrupt preemption can be modeled as merely a function call.

Based on this insight, inspired from [12] where Kidd et al. made use of a Schedule function to simulate the priority preemptive scheduler for sequentializing multi-tasking programs, we add an explicit Schedule function before each program statement of the task and ISRs in an IDP. That is, if a task or ISR consists of program statements St1, . . . , Stn, then we will get St′ 1, . . . , St′ n, where each St′ i is defined as:

\[ St′ = \text{Schedule}(); St. \]

The Schedule function works as follows: It passes through the interrupts of which the priority is higher than the current running task or ISR, and non-deterministically calls the ISR function of a higher-priority interrupt which has not yet happened. In this subsection, we will make the following assumption: Each statement in the task and ISRs is atomic and a higher-priority interrupt can happen at most once before each program statement of the task or a lower-priority interrupt. We use this assumption in this subsection to make the sequentialization method in [12] easy to understand and we will show how to remove this assumption in Sect. 3.2.

Fig. 3 shows the sequentialized program of the motivating example by adding explicit the Schedule function before each program statement of the task and ISRs. In Fig. 3, N represents the number of interrupts (and N = 1 in this example), ISRs_seq[N] (whose indices range from 1 to N) represents the corresponding sequentialized version of a fixed set of ISRs and the function nondet() non-deterministically returns true or false. The function task_seq is the entrance of the sequential program. Besides, in this example, since we have only one interrupt, the Schedule() functions added in is_seq() can be all omitted and those Schedule() functions added in task_seq() can be all replaced as

\[
\begin{align*}
\text{if(nondet()) } & \text{ ISR_seq();}
\end{align*}
\]

Figure 3: Sequentialization of the motivating example by simulating priority preemptive scheduling

3.2 Sequentializing IDPs by considering data flow dependency

In Sect. 3.1, we have described an approach to sequentialize IDPs by adding explicit calls to a Schedule function before each program statement. However, the scale of the resulting sequentialized program may become very large, especially when an IDP contains many interrupts. In this subsection, we will show how to avoiding adding unnecessary calls to the Schedule function but still guarantee the soundness of sequentialization.

Essentially, in IDPs, the task and interrupts communicate with each other through shared variables. If a program statement does not access any shared variable, it makes no difference whether an interrupt happens before or after this statement. For example, suppose that the task is comprised of St1; . . . ; Stn. Adding a call to Schedule() before each program statement will give: \{ Schedule(); St1; Schedule(); . . . ; Schedule(); Stn; \}. However, if for each i ∈ [1, n − 1] the statement Sti does not access any shared variable, the following sequentialized program is still sound:

\[
\begin{align*}
\text{St1; St2; . . . ; Stn-1;}
\end{align*}
\]

\[
\begin{align*}
\text{Schedule(); Stn;}
\end{align*}
\]

Using a loop to wrap a number of calls to the Schedule() function has a key benefit that the resulted sequentialized...
program will be of much smaller size in code lines. And loops can be analyzed very fast, for example, by using extrapolation techniques such as widening in abstract interpretation.

In fact, in practical IDPs, only a very small percentage of program statements will read/write shared variables. Moreover, the sets of shared variables between the task and different interrupts are usually different. Before a program statement \( l = g \) that reads a shared variable \( g \), we only need to consider those interrupts whose happening will affect the value of \( g \). Similarly, after a program statement \( g = l \) that writes a shared variable \( g \), we only need to consider those ISRs whose execution will be affected by the value of \( g \).

Based on this insight, we could make use of the data flow dependency information over shared variables between the task and interrupts, to avoid certain unnecessary inserted \( \text{Schedule}() \) function calls during sequentializing IDPs. To this end, we first introduce some notations.

**Data flow dependency among interrupts.** For each \( \text{ISR}_i \), we introduce \( \text{RSVars}(\text{ISR}_i) \) and \( \text{WSVars}(\text{ISR}_i) \) to respectively denote the sets of shared variables that are read and written by \( \text{ISR}_i \). Given two interrupts \( \text{ISR}_i, \text{ISR}_j \), if \( \text{RSVars}(\text{ISR}_i) \cap \text{WSVars}(\text{ISR}_j) \neq \emptyset \), we say that \( \text{ISR}_i \) is directly dependent on \( \text{ISR}_j \), denoted as \( \text{ISR}_i \rightarrow \text{ISR}_j \). Given two interrupts \( \text{ISR}_i, \text{ISR}_j \), we say that \( \text{ISR}_i \) is transitively dependent on \( \text{ISR}_j \), denoted as \( \text{ISR}_i \rightarrow^* \text{ISR}_j \), if there exists \( \text{ISR}_k \) such that \( \text{ISR}_i \rightarrow \text{ISR}_k \lor \text{ISR}_k \rightarrow \text{ISR}_i \land \text{ISR}_k \rightarrow \text{ISR}_j \). Given an interrupt \( \text{ISR}_j \), we define a so-called dependent interrupt group for \( \text{ISR}_j \),

\[ d\text{Group}[\text{ISR}_j] = \{ i \in \text{ISRs} | I \rightarrow \text{ISR}_j \}. \]

and a so-called influenced interrupt group for \( \text{ISR}_j \),

\[ i\text{Group}[\text{ISR}_j] = \{ i \in \text{ISRs} | \text{ISR}_i \rightarrow I \lor \text{ISR}_i \rightarrow \text{ISR}_j \}. \]

**Example 1.** Suppose that in an IDP, there are two shared variables \( x, y \), three interrupts \( \text{ISR}_1, \text{ISR}_2, \text{ISR}_3 \), and

\[ \text{RSVars}(\text{ISR}_1) = \{ x \} \]

\[ \text{RSVars}(\text{ISR}_2) = \{ y \} \]

\[ \text{WSVars}(\text{ISR}_1) = \{ x \} \]

\[ \text{WSVars}(\text{ISR}_2) = \{ x \} \]

Then, \( d\text{Group}[\text{ISR}_2] = \{ \text{ISR}_2 \} \) and \( i\text{Group}[\text{ISR}_2] = \{ \text{ISR}_1 \} \).

The data flow dependency relationships among ISRs can be described by a directed graph, which we call dependency graph. Each vertex of the graph denotes an interrupt and there exists a directed edge from \( \text{ISR}_i \) to \( \text{ISR}_j \) if \( \text{ISR}_i \rightarrow \text{ISR}_j \). Then the problem of computing the dependent/influenced interrupt group for \( \text{ISR}_j \) can be reduced to a reachability problem in a directed graph. We use a matrix \( DG \in \{ 0, 1 \}^{n \times n} \) to encode the graph where \( n \) is the number of interrupts, and

\[ DG_{ij} = \begin{cases} 1 & \text{if } \text{ISR}_i \rightarrow \text{ISR}_j \\ 0 & \text{otherwise} \end{cases} \]

We use a procedure \( \text{BuildDepGraph()} \) to construct the dependency graph for an IDP. And we use two procedures \( \text{CompDepGroup()} \) and \( \text{CompInfGroup()} \) to compute respectively the dependent and influenced interrupt groups for \( \text{ISR}_j \), as shown in Algorithm 1. Basically, Algorithm 1 computes the two groups by computing the transitive closure of direct dependency relations among ISRs.

**Considering only statements that access a shared variable.** As we have mentioned, if a program statement does not access any shared variable, it makes no difference whether an interrupt happens before or after this statement.

**Algorithm 1** Algorithms for computing dependent/influenced group for \( \text{ISR}_j \)

**procedure** CompDepGroup(i: int; p: int; imr: int) **returns** ws, rs: int set;

\[ ws = \{ i \}, rs = \{ \}; \]

**while** \( \{ ws \neq \emptyset \} \)

\[
\begin{aligned}
&\text{//Get an element and remove it from a set } \\
&k = \text{GetAndRemove}(ws); \quad \text{rs} \leftarrow rs \cup \{ k \}; \quad \text{for each } (j \in [p, N] \land imr) \quad \text{do} \\
&\text{if } (DG_{ki} = 1 \land k \in rs \land \{ j \}) \quad \text{do} \\
&\text{ws} \leftarrow ws \cup \{ j \}; \\
&\text{return } rs; \end{aligned}
\]

**end procedure**

**procedure** CompInfGroup(i: int; p: int; imr: int) **returns** ws, rs: int set;

\[ ws = \{ i \}, rs = \{ \}; \]

**while** \( \{ ws \neq \emptyset \} \)

\[
\begin{aligned}
&k = \text{GetAndRemove}(ws); \quad \text{rs} \leftarrow rs \cup \{ k \}; \quad \text{for each } (j \in [p, N] \land imr) \quad \text{do} \\
&\text{if } (DG_{j} = 1 \land k \in rs \land \{ j \}) \quad \text{do} \\
&\text{ws} \leftarrow ws \cup \{ j \}; \\
&\text{return } rs; \end{aligned}
\]

**end procedure**

For a program statement that reads a shared variable, we need to consider the influence from those ISRs that affect the value of this shared variable. For a program statement that write into a shared variable, we need to consider the influence of this statement to those interrupts whose executions may be affected by the value change of this shared variable.

Based on this insight, we propose the following strategy for sequentializing IDPs. We only add \( \text{Schedule}() \) functions before statements that read shared variables and after statements that write shared variables. To be more clear, we give the details as follows:

- Before a statement (in the form of \( l = g \)) that reads a shared variable \( g \), we consider invoking ISRs in \( S_1 \cup S_2 \) where

\[
S_1 = \{ i \in \text{ISRs} | g \in \text{WSVars}(I) \}
\]

\[
S_2 = \{ i \in d\text{Group}[I] | I \in S_1 \}
\]

where \( S_1 \) represents the set of ISRs that directly write shared variable \( g \) and \( S_2 \) represents the set of ISRs that are in the dependent interrupt groups of any ISR in \( S_1 \). We use procedure \( \text{ReadDepISRs()} \) to compute \( S_1 \cup S_2 \), as shown in Algorithm 2.

- After a statement (in the form of \( g = l \)) that writes a shared variable \( g \), we consider invoking ISRs in \( S_3 \cup S_4 \) where

\[
S_3 = \{ i \in \text{ISRs} | g \in \text{RSVars}(I) \}
\]

\[
S_4 = \{ i \in i\text{Group}[I] | I \in S_3 \}
\]

where \( S_3 \) represents the set of ISRs that directly read shared variable \( g \) and \( S_4 \) represents the set of ISRs that are in the influenced interrupt groups of any ISR.
In $S_1$. We use procedure $WriteInfISRs()$ to compute $S'_2 \cup S_3$, as shown in Algorithm 2.

On this basis, we introduce a new schedule function namely $ScheduleG(group)$ to non-deterministically call those ISRs in $group$, as shown in Fig. 4. According to the above strategy, we consider adding the schedule functions only before and after a statement that reads a shared variable, but we do not know how many times an interrupt may be fired before the statement $St$. In fact, in practical IDPs, an interrupt never fires too frequently in each task period, otherwise the program may disobey the real-time restriction. Especially, the system designers of real-time embedded systems often know an upper bound on the number of firing times of each interrupt during one task period. Based on this insight, to guarantee the soundness of the sequentialization following the above strategy, we add the following assumption:

- We assume that the upper bound on the number of firing times of each interrupt during one task period is given by $K$ where $K$ is a positive integer that can be $+\infty$.

In Fig. 4, we introduce a function namely $ScheduleG_K(group)$ to call the $ScheduleG()$ function $K$ times. In case where $K$ cannot be specified, we can put $K$ to $+\infty$ (and then the loop in $ScheduleG_K(group)$ becomes an unbounded loop that can stop at any time or loop forever), which can still guarantee the soundness of the sequentialization following the above strategy.

Now, we introduce functions namely $InvokeBefore(St, group)$ and $InvokeAfter(St, group)$ to insert the $ScheduleG_K(group)$ function respectively before and after a given statement $St$. During the process of sequentialization, for a statement $St^R$ that reads a shared variable, we use $InvokeBefore(St^R, group)$ to obtain the following sequentialized result:

$$St^R \equiv ScheduleG_K(group); St^R;$$

For a statement $St^W$ that writes a shared variable, we will use $InvokeAfter(St^W, group)$ to obtain the following sequentialized result:

$$St^W \equiv St^W; ScheduleG_K(group);$$

Figure 4: Scheduling functions calling only those ISRs in a given interrupt group

Simplifying the sequentialized programs. We may notice that the sequentialization method based on the above strategy may still introduce unnecessary invoking of the function $ScheduleG_K(group)$. For example, suppose the task is comprised of $St^{W_1}_1; \ldots; St^{W_n}_n$, where $St^{W_i}_i$ represents a statement that write a shared variable $g_i$ and $St^{R_i}_i$ represents a statement that read a shared variable $g_j$, while all statements in between do not access any shared variables. Then the sequentialized task will be:

$$St_1; ScheduleG_K(grp_1); St_2; St_3; \ldots; St_{n-2}; ScheduleG_K(grp_2); St_{n-1}; ScheduleG_K(grp_n); St_n$$

When the interrupt groups $grp_1$ and $grp_n$ are the same, the invoking of $ScheduleG_K(grp_n)$ is unnecessary.

Based on this insight, we design a simplification procedure $Simplify()$ to remove unnecessary invoking of $ScheduleG_K()$. The $Simplify()$ procedure removes the second invoking of $ScheduleG_K(grp_1)$ in the following two patterns:

- $St^{W}_1; ScheduleG_K(grp_1); \ldots; ScheduleG_K(grp_n); St^{R}_n$;
- $ScheduleG_K(grp_1); St^{W}_1; \ldots; ScheduleG_K(grp_n); St^{R}_n$;

where for all $i \in [2, n - 1]$ the statement $St_i$ does not write any shared variable.

3.3 Sequentializing IDPs by considering IMR

IDPs usually use an interrupt mask register (IMR) to control the interference between tasks and interrupts. Each bit of IMR corresponds to an interrupt and represents whether that interrupt is enabled or disabled. In our IDPs, programmers can use $disableISR(i)$ and $enableISR(i)$ to change the
value of IMR to disable and enable the $i$-th interrupt respectively. Hence, the value of IMR may be different at different program points.

Computing data flow dependency considering IMR. The value of IMR may affect the data flow dependency among interrupts. For example, suppose there are two shared variables $x, y$ and three interrupts $ISR_i, ISR_j, ISR_k$ where $RSVars(ISR_i) = WSVars(ISR_i) = x$ and $RSVars(ISR_j) = WSVars(ISR_j) = y$. Without considering the value of IMR, we have the following data flow dependency: $ISR_i \rightarrow ISR_j \land ISR_j \rightarrow ISR_k \land ISR_k \rightarrow ISR_i$. However, if $ISR_i$ is disabled, there is no data flow dependency among $ISR_i, ISR_j, ISR_k$.

To obtain a precise analysis of data flow dependency, we need to consider only enabled interrupts when computing the data flow dependency among interrupts. As shown in Algorithm 1 and Algorithm 2, in procedures `CompDepGroup()`, `CompInfGroup()`, `ReadDepISRs()`, `WriteInfISRs()`, we have considered the value of IMR. Essentially, these procedures consider data flow dependency among enabled interrupts. In these two algorithms, we use $inmr_i$ to represent the $j$-th bit of the $inmr$ value which indicates whether $ISR_j$ is enabled (when the bit is 1) or disabled (when the bit is 0).

Pre-analysis for analyzing the value of IMR. In order to obtain the value of IMR at each program point, we need a pre-analysis to analyze the value of IMR (for each entry function of the task and interrupts separately) before sequentializing an IDP. In other words, we need a pre-analysis for analyzing the value of IMR without considering the interleaving between tasks and interrupts. However, inside an ISR function, programmers may also call `disableISR(i)` and `enableISR(i)` to change the value of IMR. Hence, the value of IMR at the entry-point of an ISR may be different from the value at the exit-point of the same ISR. Thus, the pre-analysis that analyzes the value of IMR for each entry function of the task and interrupts separately may be not sound in general. In this paper, we essentially model interrupt preemption as a function call to the corresponding ISR. To this end, throughout this paper, we presume the following assumption:

- We assume that at the exit-point of an ISR, the IMR is reset to the initial value of IMR at the entry-point of this ISR.

In fact, this assumption is followed in most practical IDPs. Based on this assumption, we design a procedure namely `ComputeIMR()` to compute the value of IMR at each program point for each entry function of the task and interrupts separately. The value of IMR is modeled as a bit vector. For the $i$-th bit, we use 0 to represent that the $i$-th interrupt is disabled, 1 to represent that the $i$-th interrupt is enabled or inconclusive (i.e., either enabled or disabled). Note that when we can not conclude whether the $i$-th interrupt is enabled or disabled, we assign 1 to the $i$-th bit of IMR, which means that we assume the interrupt is disabled in this case. Essentially, the procedure `ComputeIMR()` performs a flow-sensitive data flow analysis using a bitwise abstract domain. For `disableISR(i)` and `enableISR(i)` statements, we set the $i$-th bit of the IMR bit-vector to 0 and 1 respectively. For the branch statement, at the control-flow join, we perform the bit-wise OR operation over the two resulting bit-vectors from different branches. In other words, for each bit, the join operation returns 0 if and only if the two corresponding input bits are 0, and otherwise returns 1.

Invoking ISRs for `enableISR(i)` and `disableISR(i)`. Until now, we have considered adding calls to the schedule function only before statements that read shared variables and after statements that write into shared variables. However, when an IDP includes statements `enableISR(i)` and `disableISR(i)`, the above strategy may miss some invocation of related ISRs. For example, Fig. 5 shows an IDP involving statements `enableISR(i)` and `disableISR(i)`, wherein $y$ is the shared variable. If we add invocation of ISRs only before statements that read shared variables and after statements that write shared variables, we will not invoke `ISR1` because `ISR1` is disabled when the shared variable $y$ is read (i.e., in line 7). However, this program may cause a division-by-zero error when `ISR1` fires between line 5 and line 6 in the `task()`.

1: int $y$;
2: void task(){
3:   int $x$, tmpy, $z$, c;
4:   $c = 1$: $x = c$;
5:   $c = 2$: $y = c$;
6:   `disableISR(1)`;
7:   `tmpy = y`;
8:   $z = 1/(x * tmpy)$;
9:   `enableISR(1)`;
10: }

Figure 5: An example with `disableISR` and `enableISR`

Hence, when dealing with statements `enableISR(i)` and `disableISR(i)`, we may also need to add an invocation of certain related ISRs. We use the following strategy to add invocation of certain related ISRs during dealing with statements `enableISR(i)` and `disableISR(i)`.

When dealing with `disableISR(i)`, we assume that all shared variables in `WSVars(ISR_i)` are read during the execution of the statement `disableISR(i)`. In this situation, we need add the schedule function to invoke `ISR_i` and all those interrupts in `dGroup(ISR_i)` before `disableISR(i)`. Similarly, when dealing with `enableISR(i)`, we presume that all shared variables in `RSVars(ISR_i)` are written during the execution of the statement `enableISR(i)`. In this situation, we need add the schedule function to invoke `ISR_i` and all those interrupts in `iGroup(ISR_i)` after `enableISR(i)`.

Algorithm 3 shows how to insert calls to related ISRs before each statement. `IMRValTbl` represents a map from each program statement to its IMR value, which is computed by `computeIMR()`. `InvokeBefore()` and `InvokeAfter()` represent a call to the corresponding interrupts before or after a statement.

3.4 The overall sequentialization algorithm considering data flow dependency and IMR

Algorithm 4 shows the overall sequentialization algorithm considering both the data flow dependency and IMR. In Algorithm 4, the procedure `SeqIDP()` is the main entry function of the overall sequentialization algorithm. $N$ is the number of interrupts. `task` and `ISR[s][N]` respectively represent the entry function of the task and interrupts. `IMRValTbl` is a hash table that maps each program statement to the value of IMR at that statement. `IMRValTbl` is computed by the procedure `computeIMR()` discussed in Sect. 3.3.

For an IDP consisting of one task and $N$ interrupts, the overall sequentialization algorithm shown in Algorithm 4 works as follows: First, we compute the value of IMR at each program point and build the data flow dependency graph.
ISR that is invoked in the sequentialized task, we do not need to initialize the task first. In most cases, the sequentialized task will be detected, since in the sequentialized task, there will be a division-by-zero error when analyzing the sequentialized IDPs, we need to analyze not only the entry function of the sequentialized ISR, but also the entry functions of those sequentialized ISRs that are never invoked in the sequentialized task.

Example 2. Suppose that an IDP is comprised of one task and two interrupts:

- \( \text{task} : \{ \text{tmp} = x; \} \)
- \( \text{ISR}_1 : \{ \text{tmp}1 = x; \text{tmp}1 = 1/\text{tmp}1; \} \)
- \( \text{ISR}_2 : \{ \text{tmp}2 = 0; x = \text{tmp}2; \} \)

where \( \text{ISR}_2 \) is of higher priority than \( \text{ISR}_1 \), \( x \) is a shared variable and \( \text{tmp}1, \text{tmp}1, \text{tmp}2 \) are non-shared variables.

Following the strategy that we only consider invoking relevant ISRs before statements reading shared variables and after statements writing shared variables, \( \text{ISR}_1 \) will never be invoked in the sequentialization result of the task. However, in this IDP, there will be a division-by-zero in \( \text{ISR}_1 \) when \( \text{ISR}_2 \) fires before \( \text{ISR}_1 \). Hence, when performing static analysis over sequentialized IDPs, we need to analyze not only the entry function of sequentialized task but also the entry function of sequentialized \( \text{ISR}_1 \). If we analyze the entry function of sequentialized \( \text{ISR}_1 \), the division-by-zero error will be detected, since in the sequentialized \( \text{ISR}_1 \) a non-deterministic call to the higher-priority \( \text{ISR}_2 \) is added before the statement \( \{ \text{tmp}1 = x; \} \).

Hence, given a sequential IDP, we first perform numerical static analysis to analyze the entry function of the sequentialized task. And then we separately analyze entry functions of those sequentialized ISRs that are never invoked in the sequentialized task.

4.2 Specific abstract domains for IDPS

To perform numerical static analysis, there exist a variety of numerical abstract domains in the literature. For example, abstract domains that are of higher priority than \( \text{ISR}_1 \), \( x \) is a shared variable and \( \text{tmp}1, \text{tmp}1, \text{tmp}2 \) are non-shared variables.
example, the interval abstract domain [7] is a kind of non-relational abstract domains and can be used to infer numerical bounds for variables, i.e., $x \in [c, d]$. The octagon abstract domain [14] is a kind of weakly relational abstract domain and can be used to infer numerical invariants in the form of $\pm x \pm y \leq c$ (where $c$ is a constant). We employ these general numerical abstract domains for analyzing IDPs.

However, sequentialized IDPs also have their own specific features that are not common in generic programs. To improve the precision of numerical static analysis of sequentialized IDPs, we need to design specific abstract domains according to the specific features of IDPs. In the following, we give an example of specific abstract domains for IDPs.

From practical IDPs, we observe that there is a specific family of interrupts which are fired after a fixed time interval. For example, some interrupts are triggered by timers. We call this kind of interrupts periodic interrupts. Furthermore, there is a kind of periodic interrupts whose periods are larger than one task period, which means that this kind of periodic interrupts are fired at most once during one task period. In this paper, we call this specific kind of interrupts as at-most.once fired periodic interrupts.

During numerical static analysis of IDPs that involve an at-most.once fired periodic interrupt ISR, whether ISR has happened or not is an important information for the precision of the analysis. However, numerical abstract interpretation often performs flow-sensitive analysis rather than path-sensitive analysis. Consider analyzing $\text{if} (\text{notdet}()) \text{ISR}()$. Let $A_i$ denote the abstract value in an abstract domain before this statement. After this statement, abstract interpretation will perform a joint operation to compute the post abstract value as $A_i \sqcup A_2$, where $A_i \sqcup \text{ISR}()$ denotes the abstract transfer function of ISR(). Intuitively, in $A_i \sqcup A_2$, $A_i$ denotes the abstract value when ISR has never been fired while $A_2$ denotes the abstract value after ISR has been fired. However, after the join operation, most numerical abstract domains will lose the information that the abstract values are different for the case where ISR has been fired or not.

Our basic idea is to use a boolean flag variable $f$ in the abstract domain to distinguish whether an at-most.once fired periodic interrupt ISR has already been fired or not. In the abstract domain, for each boolean flag variable, we maintain a pair of abstract values $(A^f, A^{\neg f})$ where $A^f$ denotes the abstract value when ISR has already been fired and $A^{\neg f}$ denotes the abstract value when ISR has not been fired. As an example, we now use the boolean flag abstract domain to analyze $\text{if} (\text{notdet}()) \text{ISR}()$. Let $(A^f_i, A^{\neg f}_i)$ denote the abstract value in the boolean flag abstract domain before this statement. After the then branch, we get the post abstract value $(\text{ISR}()^f)(A^f_i)$, $\perp$. After the else branch, nothing changes and thus we get the pair $(A^f_i, A^{\neg f}_i)$. Then, at the control-flow join, we perform a joint operation to compute the post abstract value as

$$(\text{ISR}()^f)(A^f_i), \perp) \sqcup (A^f_i, A^{\neg f}_i)$$

and then by element-wise join, it will result in

$$(A^f_i \sqcup \text{ISR}()^f)(A^f_i), A^{\neg f}_i)$$

**Example 3.** Suppose that an IDP is comprised of one task and one interrupt where $x$ is a shared variable, all other variables are non-shared variables and ISR is an at-most.once fired periodic interrupt:

- **task:** $\{x = 0; \; tx = x; \; tx = tx + 1; \; x = tx; \; z = x; \}$
- **ISR:** $\{tx = x; \; tx = tx + 10; \; x = tx; \}$

If we use the interval abstract domain to analyze the program, at the end of the task, the resulting variable bounds are $(x \in [1 ,21], z \in [1, 21])$. However, if we use the boolean flag abstract domain on top of intervals, at the end of the task, the results will be $(x \in [11, 11], z \in [11, 11])$ when ISR has been fired and $(x \in [1, 1], z \in [1, 1])$ when ISR has not been fired. Obviously, the results given by the boolean flag abstract domain are more precise.

## 5. IMPLEMENTATION AND EXPERIMENT RESULTS

We have implemented a prototype tool to sequentialize IDPs, which uses CIL [18] as its front-end. We use a CIL supported inline tool to deal with function calls. We have also developed a numerical static analyzer for analyzing sequentialized IDPs based on the front-end CIL and the Apron [11] numerical abstract domain library.

Our experiments were conducted on a selection of benchmark examples listed in Fig. 6. *Motv_Ex* is the motivating example shown in Fig. 1. *DataRace_Ex* and *Privatize* come from a data race detection tool Goblint [21]. *Nxt gs* is a robot controller program from LEGO company samples. *UART* (Universe Asynchronous Receiver and Transmitter) is from an open source website which implements a First-In First-Out (FIFO) buffer. *Ping_pong* is an implementation of ping-pong buffer (or double buffering that is a technique to use two buffers to speed up a computer that can overlap I/O with processing). Some of these examples originally do not include interrupts, such as *Nxt_gs*, but tasks in these programs are scheduled by the priorities of tasks, which is quite similar to IDPs. Thus we adapt them into IDPs.

Fig. 6 shows the sequentialization results of all the benchmarks. OLT and OLI represent respectively the original code size in lines of task and interrupts. #Vars represents the number of variables in programs. #ISR represents the number of interrupts. SEQ represents the sequentialization method described in Sect. 3.1 which is inspired from [12]. DF_SEQ represents the sequentialization method described in Sect. 3.4 which considers data flow dependency and IMR. From the results, we can see that the code size of the program given by DF_SEQ is much smaller than that given by SEQ. For example, for UART, the code size of the program given by DF_SEQ is around 20% of the code size of that given by SEQ.

Fig. 7 shows the analysis results of analyzing sequentialized IDPs by numerical abstract interpretation. We use box and octagon abstract domains to analyze the sequentialized IDPs. For all the examples in Fig. 7, using the box domain and the octagon domain for both the programs given by SEQ and DF_SEQ can find the same properties or errors in the program. For *Motv_Ex*, we find the expected division-by-zero error. For *DataRace_Ex* and *Privatize*, our method can prove their assertions. For example, *Privatize* asserts that a shared variable is always equal to 1. For

1http://lejos-osek.sourceforge.net/

2http://www.mikrocontroller.net/topic/101472#882716
### Related Work

**Sequentialization.** Much work has been done on sequentializing concurrent programs. Qadeer et al. [19] propose a context bounded analysis (CBA) method for concurrent programs via sequentialization. Their sequentialization method employs a non-deterministic scheduler model for two threads and two context switches. Lal et al. [13] propose a CBA method based on sequentialization with an arbitrary given context bound. Inverso et al. [10] propose a lazy sequentialization method that reduces the nondeterminism of sequentialized programs to avoid exponentially growing formula sizes during model checking the sequentialized programs. Recently, Chaki et al. [5] present a CBA method for analyzing periodic programs based on sequentialization.

Kidd et al. [12] propose a sequentialization method for priority preemptive scheduling systems in which each task is periodic. The key idea is to use a single stack for all tasks and model preemptions by function calls. Edwards [9] surveys a variety of approaches for translating concurrent specifications (these concurrent specifications are more abstract than concurrent programs) into sequential code which can be efficiently executed.

Compared with the above work, our sequentialization method is specifically for IDPs. Moreover, our method makes use of the data flow dependency among tasks and interrupts to reduce the size of the sequentialized program. In addition, we consider analyzing numerical properties of the sequentialized programs using numerical abstract interpretation.

**Numerical static analysis of embedded software.** Most of the existing numerical static analysis approaches consider sequential programs. Astree [2] is one of the famous numerical static analyzers for sequential programs, which has been successfully used in analyzing flight control software.

Miné [15, 16] proposes a numerical static analysis method for parallel embedded software. The main idea of his method is to iterate each thread in turn until all thread interferences stabilize. Compared with his work, our work is specially for IDPs and we can get more precise analysis results for IDPs.

Cooprider et al. [6] propose a static analysis method for embedded software to reduce the code size. BeckSchulze et al. [1] propose a data race analysis method for lockless microcontroller programs considering hardware architecture. Compared with their work, our method focuses on numerical properties of IDPs and considers data flow dependency among tasks and interrupts. Monniaux [17] proposes a static analysis method for a concurrent USB driver, which is limited to two threads. Compared with his method, our method supports multiple tasks and interrupts.

**Analysis of interrupt-driven programs.** In the literature, there are a few work on analyzing and verifying IDPs [3, 4, 20, 21]. Brylow et al. [3] propose a static analysis method for interrupt-driven Z80-based software. Their method uses model checking to analyze upper bounds of stack size and interrupt latencies of IDPs. Most of the existing work focus on object code and consider problems such as interrupt latency, stack size, and data race.

Compared with the above work, our method analyzes the source code of IDPs rather than object code and focuses on numerical properties of IDPs.

### Conclusion

We have presented a sound numerical static analysis approach for IDPs. The key idea is to sequentialize IDPs into sequential programs before analysis. The idea of sequentializing IDPs into sequential programs enables the use of existing analysis and verification techniques (e.g., bounded model checking, symbolic execution, etc.) for sequential programs to analyze and verify IDPs. We have proposed a sequentialization algorithm specifically for IDPs, by considering the data flow dependency among ISRs and specific hardware features of IDPs. After that, we have shown how to use numerical abstract interpretation to analyze numerical properties of IDPs.
properties of the sequentialized IDPs. By considering specific features of sequentialized IDPs, we design and make use of specific abstract domains to analyze sequentialized IDPs. The preliminary results show that our method is promising. For future work, we will consider designing more specific abstract domains that fit IDPs and conducting more experiments on large realistic IDPs. We also plan to handle shared variables involving pointers during sequentialization.

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8. REFERENCES