Checkpointing and Localized Recovery for Nested Fork-Join Programs

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Abstract—While checkpointing is typically combined with a restart of the whole application, localized recovery permits all but the affected processes to continue. In task-based cluster programming, for instance, the application can then be finished on the intact nodes, and the lost tasks be reassigned.

This extended abstract suggests to adapt a checkpointing and localized recovery technique that has originally been developed for independent tasks to nested fork-join programs. We consider a Cilk-like work stealing scheme with work-first policy in a distributed memory setting, and describe the required algorithmic changes. The original technique has checkpointing overheads below 1% and negligible costs for recovery, we expect the new algorithm to achieve a similar performance.

I. INTRODUCTION

Checkpoint/Restart (C/R) is the current standard technique to handle fail-stop failures of processes in clusters [1], [2]. It is often criticized for limited scalability, and therefore variants such as uncoordinated [3], in-memory [4] and multi-level [5] checkpointing have been devised. These variants reduce the costs, but most systems still require to restart the whole application when a failure occurs.

From both a deployment and performance point of view, it may be preferable to continue the program execution on the reduced set of processes, which is called shrinking recovery. Related to that, a localized recovery approach confines the failure handling to the affected processes, ideally without any involvement of the others.

A few localized, and partly shrinking, recovery techniques have already been suggested, notably in the context of task-based parallel programming [6]–[8]. This context is generally promising for the provision of resilience: Since tasks have clearly defined interfaces, checkpointing at the task level allows to nicely combine ease-of-use and efficiency. Thereby ease-of-use is achieved through a transparent implementation in the runtime system, and efficiency through saving task descriptors only.

The importance of task-level checkpointing is likely to increase with the current rise of task-based parallel programming (e.g. [9]–[16]). While the cited environments differ widely in their mechanisms for task creation and cooperation, this paper solely refers to nested fork-join programs (NFJs), which were popularized with Cilk [17]–[19]. Listing 1 depicts the computation of Fibonacci numbers as an example.

Listing 1: Nested fork-join program

```c
int fib(int n) {
    if (n < 2) return n;  // 0
    int x = spawn fib(n-1);  // 1
    int y = spawn fib(n-2);  // 2
    sync;  // 3
    return x + y;
}
```

NFJs start with a single root task, here `fib(n)`. Then each task may spawn any number of children and pass parameters to them. A task must wait for the results of all children, either explicitly with `sync`, or implicitly at the end of the function. We assume that the tasks communicate through parameter passing and result return only, they must not have side effects.

The execution of a fork-join program gives rise to a tree, such as the one in Figure 1. In the figure, rectangles denote spawned functions. Numbers 0 to 3 correspond to sequential code sections as given by the comments in Listing 1. For instance, section 0 runs from the beginning of the function until the spawn of the first child. Downward edges (solid) mark spawns, and upward edges (dotted) mark result returns at explicit or implicit `sync`'s. NFJ implementations commonly use work-first work stealing, which is explained in Section II.

Fig. 1: Execution of nested fork-join programs

A resilience scheme with shrinking localized recovery for NFJs under work-first work stealing has already been introduced by Kestor et al. [7]. Their technique exploits the particular NFJ style of synchronization to restrict task re-execution to the lost (sub-)tasks. More specifically, when \( k \) out of \( p \) processes fail, a share of \( k/p \)-th of the previous work must be re-done on average. The technique has overheads below 1% in failure-free runs, but some drawbacks in recovery:
Unlike on average, up to 100% of the previous work must be re-done in worst-case scenarios. These occur when the root of a large (sub-)tree fails at the moment when all results have been returned there. To avoid such unlimited information loss, the authors of [7] suggest to combine their technique with standard C/R, which however means to essentially give up localized recovery.

- When a failure occurs, all processes must inspect a data structure and participate in a global reduction, deviating from perfectly localized recovery.
- The average share of $k/p$ may still be large for long-running programs in failure-prone environments.

Therefore, this paper advocates a checkpointing-based alternative. Checkpointing algorithms already exist for other classes of task-based parallel programs [6], [20]. We refer to an algorithm for dynamic independent tasks (DIT) from Posner et al. [8], and adapt it to NFJ. Like NFJ tasks, DIT tasks are spawn dynamically, forming a tree. However, child tasks do not return a result to their parent, but contribute to a final result that is accumulated locally and calculated by reduction.

A recent study has compared the algorithms from Kestor et al. [7] and Posner et al. [8] in DIT, to which the NFJ algorithm was transferred [21]. The study reported overheads below 1% for both algorithms, with those of the NFJ-specific algorithm [7] being lower in failure-free cases, and those of the checkpointing algorithm [8] being lower during recovery. We expect similar results for NFJ, since the algorithm proposed in this paper closely resembles the original one.

Section II of this abstract states our assumptions on the failure model and provides background on work stealing. Then Section III sketches the checkpointing algorithm and explains our proposed algorithmic changes. Section IV outlines some related work, and Section V finishes with conclusions.

II. BACKGROUND AND ASSUMPTIONS

a) Failure Model: We consider fail-stop failures of processes after permanent hardware failures, and assume reliable network communication. Any number of failures may strike at any time, including simultaneous failures and failures during recovery. A program must always compute the correct result, except that it may abort when the resilient store used for checkpoint saving (see Section III) fails. All processes must be notified of all failures, possibly with a delay.

b) Work stealing: Tasks are commonly executed by a fixed set of workers, which in our distributed memory setting correspond to processes. Each worker owns a local pool for storing and retrieving tasks, which are represented by stack frames. When the pool is empty, the worker becomes a thief and tries to steal tasks from a victim, e.g., from a random worker. Like [7], we consider private pools, i.e., the thief must send a request message for that, and the victim answers by sending loot [22], [23].

An NFJ execution starts with one local pool holding the root task. Then, most implementations proceed in a work-first manner: When a worker encounters a spawn, it branches into the child and puts the continuation of the parent frame into the pool. Steals always extract the oldest frame.

Figure 2 illustrates work-first work stealing. The figure uses the same notation as Figure 1 but a different task structure to facilitate further discussion. Each color marks the work performed by a particular worker.

The computation starts with the green worker (called Green) processing the A frame. At the first spawn, Green branches into B, and Brown steals the continuation of A. In general, thieves process parent frames, and victims process children, as shown on the right side of the picture.

There are only few cluster implementations of the above scheme [7], [18]. The one in [7] uses active messages in a Partitioned Global Address Space (PGAS) setting. When a thief encounters a sync, it sends the frame back to the victim (or transitively to all victims) for result matching. Note that the parent frame is sent back to the child (and not vice versa), even though the arrows in Figure 2 indicate that logically the result is incorporated into the parent frame. When a victim finishes a task whose parent is away, it locally saves the result and steals a new task.

For an example, consider Red in Figure 2 It stole frame B from Green at B2, and was stolen from by Yellow at B3. Red finished F before Yellow returned. So Red kept the result (called $\text{xF}$) and stole the A frame at A3. Later, Blue stole the A frame at A4 and already returned it (called $\text{fA}$) at the sync opening A5 (as marked by the dotted red line). Now consider the time when all sections printed in bold have been finished, i.e., right before branching into H. At this time, Red holds $\text{xF} \text{, fA}$, a local pool with D2 and G2, and a descriptor of H. Furthermore, Red knows the identities of all victims and thieves with still unmatched results: Green and Yellow for the B2 frame, and Brown and Blue for the A3 frame. In its entirety, this information forms Red’s state, which will be defined in Section III.

III. CHECKPOINTING ALGORITHM

We refer to the AllFT algorithm from Posner et al. [8], which is the simplest of three DIT algorithms suggested in that reference. Our techniques may extend to their incremental scheme, which reduces the overhead for large task descriptors.

AllFT regularly writes uncoordinated checkpoints to a resilient store. Reference [8] uses the IMap of Hazelcast [24] for this purpose, which is a replication-based in-memory store,
but the algorithm is not restricted to it. Checkpoints for DIT comprise the local pool contents and the accumulated worker result. They are written between finishing one task and starting the next one, so that they capture a coherent state. Beside regular checkpoint writing, AllFT updates the checkpoints at each steal. A resilient steal protocol ensures consistency between victim, thief, and their respective checkpoints, despite possible failures [8].

For recovery, each worker has a designated buddy worker. The buddy reads the last checkpoint of the failed worker from the resilient store, and stores the saved tasks into its own pool. This way, all recently run tasks of the failed worker are re-executed. Moreover, the buddy takes care of any recently extracted loot from the failed worker. Only relevant in [8], it does not adopt the accumulated result, which is kept in the resilient store instead.

Buddies are chosen to be the next worker alive in a ring of workers, using some numbering of workers. If a buddy fails, its successor takes its role. Like stealing, task adoption is protected by a resilient recovery protocol.

Details of the steal and recovery protocols can be found in [8], [25]. Briefly stated, they consider specific cases and for each define a set of actions to be taken to get back to a consistent state [8]. For instance, a victim may have to take back tasks when the thief fails. Outside the protocols, the checkpointed state of a worker is always consistent with the ongoing computation. Thus, one may safely reset a worker’s state to the checkpointed one, without adjusting the states of the others.

The above algorithm can be adapted to NFJ with only two major changes:

1. The contents of the checkpoints must be equated to the state of an NFJ worker, as defined below.
2. An additional frame return protocol is required.

As in [8], checkpoints are written independently for each worker and contain the worker’s state. Since they are written between task processings, they need not include the internal state of a current task. We define the state of a worker to consist of:

- the current contents of W’s local pool,
- all locally saved task results at W that have not yet been incorporated into their parent frame (e.g., \( rF \)),
- all frames returned to W from their thieves that are awaiting result incorporation (e.g., \( fA \)),
- the identities of all victims of W to which W has not yet returned the respective stolen frame,
- the identities of all thieves of W that have not yet returned their frame to W, and
- if relevant, a task descriptor of the next task.

The last item is relevant in the following case 1 of possible occasions for checkpoint writing, but not in case 2. When a checkpoint is due, whichever of these two occasions comes first applies:

1. right before branching into a child or into a stolen task (e.g. before branching into H), or 2. after finishing a task and incorporating its result into the parent frame or storing it locally (e.g. after finishing H and incorporating its result into the G frame).

In case 2, the descriptor of the next task is irrelevant, since it will either be a task from the local pool, which is part of the state anyway; or a newly stolen task, for which the steal protocol will schedule another checkpoint.

The steal and restore protocols can essentially be taken from [8], [25], since the handshaking to reach consistency is independent from the contents of checkpoints. Merely a few differences exist in the way in which the buddy worker adopts the failed worker’s data. Most importantly, for stored results like \( rF \), it must inform the thief (in the example: Yellow) about the result’s new location. This is feasible since the identities of the thieves are contained in the adopted checkpoint. If the thief has failed as well, the buddy contacts the buddy of the thief instead, which has adopted or will adopt the stolen frame or a continuation thereof. The identity of the thief’s buddy can be figured out easily, since it is the next worker alive in the ring of workers.

Reference [8] does not specify a frame return protocol, since DIT has no result return. However, frame return resembles stealing insofar as data (a result or loot, respectively) are moved from one worker to another. Therefore, a subset of the steal protocol from [8] (starting after receipt of the steal request) can be used for this purpose. The protocol includes two checkpoints and a temporary frame saving in the resilient store.

IV. RELATED WORK

There has been growing interest in task-level resilience in recent years. Topics include task re-execution after silent errors [26–29], techniques to handle different failure types together [30], and the tracking of global data accesses of tasks [31]. While we focus on the recovery of a dynamic task structure, Lion and Thibault [6] concentrate on checkpointing the data that are communicated between tasks. Like us, they perform a localized recovery, as do all previously discussed NFJ and DIT resilience schemes and their precursors [7], [8], [18–20], [25], [32].

Outside task-level resilience, localized recovery has been realized for MPI programs [33–35], with the help of Fenix [36] and User Level Failure Mitigation (ULFM) [37]. Another resilient in-memory store than the IMap was discussed in [38].

V. CONCLUSIONS

This extended abstract has suggested a checkpointing algorithm for NFJs, which supports shrinking localized recovery from one or multiple fail-stop failures of processes. It is a variant of a previous algorithm for DIT with only few changes that chiefly regard the contents of checkpoints. Therefore we expect the new algorithm to perform similarly to the original one, which causes less than 1% running time overhead and neglectable costs for recovery. Future work should experimentally investigate this expectation.
