MATCH: An MPI Fault Tolerance Benchmark Suite

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Abstract—MPI has been ubiquitously deployed in flagship HPC systems aiming to accelerate distributed scientific applications running on tens of hundreds of processes and compute nodes. Maintaining the correctness and integrity of MPI application execution is critical, especially for safety-critical scientific applications. Therefore, a collection of effective MPI fault tolerance techniques have been proposed to enable MPI application execution to efficiently resume from system failures. However, there is no structured way to study and compare different MPI fault tolerance designs, so to guide the selection and development of efficient MPI fault tolerance techniques for distinct scenarios. To solve this problem, we design, develop, and evaluate a benchmark suite called MATCH to characterize, research, and comprehensively compare different combinations and configurations of MPI fault tolerance designs. Our investigation derives useful findings: (1) Reinit recovery in general performs better than ULFM recovery; (2) Reinit recovery is independent of the scaling size and the input problem size, whereas ULFM recovery is not; (3) Using Reinit recovery with FTI checkpointing is a highly efficient fault tolerance design. MATCH code is available at https://github.com/kakulo/MPI-FT-Bench.

I. INTRODUCTION

As supercomputers continue to increase in computational power and size, next-generation HPC systems are expected to incur a much higher failure rate than current systems. For example, the Sequoia supercomputer located in Lawrence Livermore National Laboratory (LLNL) reported a mean time between node failures of 19.2 hours in 2013 [1]. After that, in 2014, the Blue Waters supercomputer reported a mean time between node failures of 6.7 hours [2]. Most recently, the Taurus system located in TU Dresden reported a mean time between node failures of 3.65 hours [3].

This trend raises concerns in the HPC community for MPI applications running on tens of thousands of processes and nodes, that are prone to fail due to the increased probability of a failure. Process and node failures frequently occur in production HPC systems due to power outages and other issues. MPI process and node failures are usually fail-stop failures. In this type of failure, application execution cannot continue without repairing the communication and has to stop.

These crucial facts lead to increasing importance of and challenges for developing efficient and effective fault tolerance designs for scaling HPC systems [4, 5]. There are numerous fault tolerance techniques proposed to protect MPI application execution from system failures. MPI fault tolerance techniques can be assigned into two types of different focus. Checkpointing [6, 7, 8, 9, 10], commonly used in HPC applications, is one type of fault tolerance technique that focuses on restoring application state. Checkpointing takes place in two separate phases: storing the system state and recovering from it in case of a failure. Checkpointing helps MPI applications quickly restore application state from the latest checkpoints through saving application execution state periodically. The other type of MPI fault tolerance technique focuses on restoring the MPI state. Restarting is a baseline solution for restoring the MPI state, which immediately restarts an application after execution collapses due to a failure. Later, because of the inefficiency of restarting an application, HPC practitioners propose MPI recovery mechanisms to restore the MPI state online. User-level Fault Mitigation (ULFM) [11] and Reinit [12, 13, 14] are the two pioneering MPI recovery frameworks in this effort. ULFM supports a wide range of recovery strategies, including local forward recovery and global-restart recovery, whereas Reinit only supports global-restart recovery. ULFM is a powerful MPI recovery framework but complicated to use. In contrast, Reinit requires less programming effort.

However, there is no existing framework that enables a comprehensive comparison between different MPI fault tolerance techniques. To solve the problem, we design and develop a benchmark suite called MATCH, aiming to study the performance efficiency of different MPI fault tolerance configurations. MATCH contains six proxy applications from the Exascale Computing Project (ECP) Proxy Apps Suite and LLNL Advanced Simulation and Computing (ASC) proxy application suite; MATCH uses Fault Tolerance Interface (FTI) [15] for data recovery and uses ULFM and Reinit for MPI recovery. We pick a representative set of HPC applications, but our methodology is extensible to other HPC applications too. In evaluation, we break down the execution time and compare the performance overhead when using FTI with Restart, when using FTI with ULFM, and when using FTI with Reinit, respectively. All the above experiments are running in four different scaling sizes (64 processes, 128 processes, 256 processes, and 512 processes on 32 nodes), in three different input sizes (small, medium, and large), and with or without injecting process failures.

In particular, our contributions are:
1) We present MATCH, an MPI fault tolerance benchmark suite. This is the first benchmark suite designed for MPI fault tolerance. We illustrate the process and manifest the details of implementing three different fault tolerance designs to HPC proxy applications.
2) To facilitate checkpointing, we propose three principles to automatically detect data objects for checkpointing. Those data objects are the only necessary data objects to guarantee the application execution correctness after
restoring the application state.

3) We comparatively and extensively investigate the performance efficiency of different fault tolerance designs. Our evaluation reveals that, for MPI global-restart recovery, using FTI with Reinit is the most efficient design within the three evaluated fault tolerance designs, and Reinit recovery is four times faster than ULFM recovery on average, and 16 times faster than Restart on average.

II. BACKGROUND

A. MATCH

There is no existing benchmark suite aiming at benchmarking of MPI fault tolerance. We design, implement and test the benchmark suite MATCH to understand and comparatively study the performance efficiency of different MPI fault tolerance designs. MATCH is composed of six HPC proxy applications, taken from widely used HPC benchmark suites, aiming to represent the HPC application domain. Our fault tolerance design has two interfaces: the checkpointing interface to preserve and protect application data, and the failure recovery interface to protect and repair the MPI communicator. We use the Fault Tolerance Interface (FTI) for checkpointing, and Restart, ULFM, and Reinit for MPI process recovery.

B. Workloads

Our workloads comprise of proxy applications present in well-known benchmark suites: ECP proxy applications suite [16] and LLNL ASC proxy applications suite [17]. Proxy applications are small and simplified applications that allow HPC practitioners, operators, and domain scientists to explore and test key features of real applications in a quick turnaround fashion. Our workloads represent the most important HPC application domains in scientific computing, such as iterative solvers, multi-grid, molecular dynamics, etc. We describe the six proxy applications used in MATCH below.

AMG: An algebraic multi-grid solver dealing with linear systems in unstructured grids problems. AMG is built on top of the BoomerAMG solver of the HYPRE library which is a large-scale linear solver library developed at LLNL. AMG provides a number of tests for a variety of problems. The default one is an anisotropy problem in the Laplace domain.

CoMD: A proxy application in Molecular Dynamics (MD) commonly used as a research platform for particle motion simulation. Different from previous MD proxy applications such as miniMD, the design of CoMD is significantly modularized which allows performing analyses on individual modules.

LULESH: A proxy application that solves the hydrodynamics equation in a Sedov blast problem. LULESH solves the hydrodynamics equation separately by using a mesh to simulate the Sedov blast problem which is divided into a composition of volumetric elements. This mesh is an unstructured hex mesh, where nodes are points connected by mesh lines.

miniFE: A proxy application that solves unstructured implicit finite element problem. miniFE aims at the approximation of an unstructured implicit finite element.

miniVite: A proxy application that solves the graph community detection problem using the distributed Louvain method. The Louvain method is a greedy algorithm for the community detection problem.

HPCCG: A preconditioned conjugate gradient solver that solves the linear system of partial differential equations in a 3D chimney domain. HPCCG approximates practical physical applications that simulate unstructured grid problems.

C. Checkpointing Interface - FTI

Fault Tolerance Interface (FTI) [18] is an application-level, multi-level checkpointing interface for efficient checkpointing in large-scale high-performance computing systems. FTI provides programmers a API, which is easy to use and the user can choose a checkpointing strategy that fits the application needs. FTI enables multiple levels of reliability with different performance efficiency by utilizing local storage, data replication, and erasure codes. It requires users to designate which data objects to checkpoint, while hiding any data processing details from them. Users need only to pass to FTI the memory address and data size of the date object to be protected to enable checkpointing of this data object. Because failures can corrupt either a single or multiple nodes during the execution of an application, FTI provides multiple levels of resiliency to recover from failures of different severity. Namely, the levels are the following:

- L1: This level stores checkpoints locally to each compute node. In a node failure, the application states cannot successfully be restored.
- L2: This level is built on top of L1 checkpointing. In this level, each application stores its checkpoint locally as well as to a neighboring node.
- L3: In this level, the checkpoints are encoded by the Read-Solomon (RS) erasure code. This implementation can survive the breakdown of half of the nodes within a checkpoint encoding group. The lost data can be restored from the RS-encoded files.
- L4: This level flushes checkpoints to the parallel file system. This level enables differential checkpointing.

FTI has proposed a multi-level checkpointing model, and have conducted an extensive study of correctness and reliability of this proposed checkpointing model. In our work, for the first time, we use FTI in the context of MPI recovery.

D. Failure Recovery Interface - ULFM and Reinit

MPI failure recovery has multiple modes, including global, local, backward, forward, shrinking, and non-shrinking.

Global: The application execution must roll back all processes (including survivor and failed processes) to a global state to fix a failure.

Local: The application can continue the execution by repairing only the failed components, such as the failed processes, to continue the execution.

Backward: The application execution must go back to some previous correct state to survive a failure.
Forward: The failure can be fixed with the current application state, and the execution can continue.

Non-shrinking: The application needs to bring back all failed processes to resume execution.

Shrinking: The application execution is able to continue with the remaining survivor processes.

We target global, backward, non-shrinking recovery in this work, because this recovery fits best for the widely used Bulk Synchronous Parallel (BSP) paradigm of HPC applications.

1) ULFM: User-level Fault Mitigation \cite{11} is a leading MPI failure recovery framework providing shrinking recovery and non-shrinking recovery. ULFM develops new MPI operations to add fault tolerance functionalities. These functionalities include fault detection, communicator repairing, and failure recovery. Particularly, ULFM leverages the MPI error handler to provide notification of process failures. Once a failure is detected, the notified applications invokes ULFM to issue the operation MPI_Comm_revoke(), which revokes processes in the communicator. This operation interrupts any pending communication for this communicator for all member processes. ULFM then removes the failed processes using an operation MPI_Comm_shrink(), which creates a new communicator consisting only of survivor processes. Shrinking recovery is done using the steps described above. For non-shrinking recovery, ULFM further uses the MPI_Comm_spawn() operation to spawn new processes and create a new communicator. ULFM then uses the MPI_Intercomm_merge() operator to merge the communicator of survivor processes and the communicator of spawned processes to create a new, combined communicator. We provide a sample implementation of ULFM non-shrinking recovery in Figure 3.

2) Reinit: Reinit \cite{13}, \cite{14}, \cite{19} is an alternative recovery framework designed particularly for global backward non-shrinking recovery. Reinit implements the recovery process into the MPI runtime, thus it is transparent to users. Therefore, the programming effort of using Reinit is much less than using ULFM. Programmers only need to set a global restart point. The remaining recovery is done by Reinit. Reinit is much more efficient than ULFM because MPI recovery transparently handled in MPI runtime \cite{14}, whereas ULFM recovery is handled not only in MPI runtime but also in the application.

III. DESIGN

We present design details in this section. In particular, we describe the algorithm that we use to find data objects for checkpointing through data dependency analysis.

A. Find Data Objects for Checkpointing

Unlike many fault tolerance frameworks that request programmers to decide data objects for checkpointing, we develop a practical analytic tool to guide programmers to identify data objects that must be checkpointed to recover the application execution to the same state as before the failure. We identify data objects for checkpointing through data dependency analysis across iterations following three principles.

1) The data objects for checkpointing across iterations must be defined before the iterative computation. Data objects defined locally within the main computation loop are excluded from checkpointing.
2) The data objects for checkpointing must be used (read or written) across iterations of the main computation loop.
3) The value of data objects for checkpointing must vary across iterations of the main computation loop.

Following the three principles, we design and develop a data dependency analysis tool. The input to the tool is a dynamic execution instruction trace generated using LLVM-Tracer \cite{20}. The trace contains detailed information of dynamic operations, such as the register name and memory address, the operator, and the line number in the source code where the operation performs. We describe the algorithm of the data dependency analysis tool in Algorithm 1. The input to the algorithm is the set of locations used within the main computation loop and the set of locations allocated before the main computation loop. Those locations are either registers or memory locations. We create the two sets of locations by traversing the instruction trace once. After that, we first check values of locations and make sure the invocation values of the same location within the main computation loop are different. We then remove repetitions from both sets of locations. Lastly, for each location in the set of the main computation loop, we search for a match in the location set before the main computation loop. If a match is found, the matched location is used to localize data objects for checkpointing. The output of the tool is a set of locations for checkpointing. Note that the tool only outputs the locations for checkpointing, runs separately, and does not support automatic generation of checkpointing code at this stage, which we leave as future work.

IV. IMPLEMENTATION

A. FTI Implementation

The Fault Tolerance Interface (FTI) is a checkpointing library widely used by HPC developers for checkpointing. We illustrate a sample usage of FTI in Figure 1. Please read the FTI paper \cite{15} for the implementation details of FTI function calls such as FTI_Protect() and FTI_Recover(). We reckon a challenge while implementing checkpointing using FTI for MATCH workloads.

The challenge is the programming complexity of enabling FTI checkpointing to data objects when the number of data objects for checkpointing is large. FTI requests users to add FTI checkpointing to every data object manually. This significantly increases the programming effort when the number of data objects for checkpointing is large and when the data object is a complicated data structure. This is a common issue in application-level checkpoint libraries such as FTI, VeloC, and SCR. These libraries cannot automatically enable checkpointing to target data objects.

B. FTI with Reinit Implementation

Reinit is the state-of-the-art MPI global non-shrinking recovery framework. Reinit hides all of the recovery implementation
in the MPI runtime, which makes it ease-to-use. We provide a sample implementation of Reinit with FTI checkpointing in Figure 2. We can see that Reinit recovery only adds less than five lines of code. Line 4 and 5 are for Reinit recovery, while Line 14 is used for other functions. FTI is completely independent of Reinit. To implement FTI with Reinit, the only thing to notice is to move the FTI_Init() and FTI_Finalize() functions into the resilient_main() function as well. Please read work on Reinit [13], [14], [19] for the design and implementation details of Reinit.

C. FTI with ULFM Implementation

ULFM is a pioneer MPI recovery framework. ULFM provides five new MPI interfaces to support MPI fault tolerance. ULFM gives the flexibility to programmers to use provided interfaces to implement their own, customized MPI recovery strategy. Also, ULFM allows programmers to use both shrinking and non-shrinking recovery. However, it takes a significant learning and programming effort before a programmer can successfully implement recovery with ULFM. As most HPC applications follow the Bulk Synchronous Parallel (BSP) paradigm, we focus on ULFM global non-shrinking recovery. In order to implement ULFM non-shrinking recovery, we add more than 200 lines of code for each benchmark, which requires more effort compared to the implementation (less than five lines of code) using Reinit for recovery. We provide a sample implementation of ULFM global non-shrinking recovery with FTI in Figure 3.

When combining ULFM global non-shrinking recovery with FTI, it is important to notice that the MPI_COMM_WORLD must be implemented as a global variable with an external declaration. See Lines 2-6 in Figure 3 for the implementation details. This is because ULFM updates the world communicator handler and FTI must use the repaired world communicator for MPI communication to correctly function.

D. Fault Injection

We emulate MPI process failures through fault injection. In particular, we raise a SIGTERM signal at a randomly
selected MPI process in a randomly selected iteration of the main computation loop. We illustrate the fault injection code in Figure 4. Note that we choose to evaluate different fault tolerance techniques by triggering a process failure, which does not mean that the MPI recovery frameworks do not support recovery from a node failure. On the one hand, Reinit can recover from a node failure [14], on the other hand, the current ULFM implementation cannot. In our case, it is sufficient to evaluate on MPI process failures to compare the performance difference when using FTI checkpointing in ULFM and Reinit.

We measure and compare the MPI failure recovery time, the checkpointing time, and the application execution time of three fault tolerance designs. We use a similar methodology with other works [14], [21], [22], [23] to evaluate MPI fault tolerance, we validate our benchmark suite MATCH on four scaling sizes and three input problem sizes, both with and without fault injection. We answer the following questions:

• Can fault tolerance interfaces (such as ULFM) delay the application execution or not?
• Can the checkpointing interface and the MPI recovery interface interfere with each other?
• Can ULFM perform better or Reinit perform better for different scaling sizes and different input problem sizes?

A. Artifact Description

We run experiments on a large-scale HPC cluster having 752 nodes. Each node is equipped of two Intel Haswell CPUs, 28 CPU cores, 128 GB shared memory, and 8 TB local storage.

B. Experimentation Setup

This section provides details of the experimentation setup. We evaluate three fault tolerance designs. Those are FTI checkpointing with Restart (RESTART-FTI) which means that we restart the execution, in case of a failure, for MPI recovery, FTI checkpointing with Reinit recovery (REINIT-FTI), and FTI checkpointing with ULFM recovery (ULFM-FTI).

For FTI checkpointing, we use its L1 mode. FTI L1 mode allows to store checkpoints to the local SSD or to do in-memory checkpointing. We use the fastest approach that saves checkpoints to the local memory using RAMFS through “/dev/shm”. Although there are also L2, L3, and L4 modes for checkpointing, we do not evaluate all of them. The efficiency comparison between the four FTI checkpointing modes has been thoroughly studied in the FTI paper [18]. We save checkpoints every ten iterations. For ULFM, we use the latest version “ULFM v4.0.1ulfm2.1rc1” based on Open MPI 4.0.1. For Reinit [14], we use its latest version based on Open MPI 4.0.0.

We implement all the three fault tolerance designs in the MATCH workloads. Each design is run on three input problem sizes with the default scaling size (64 processes) with and without fault injection. Each design is also executed on four scaling sizes (64 processes on 32 nodes, 128 processes on 32 nodes, 256 processes on 32 nodes, and 512 processes on

Fig. 3: A sample implementation of ULFM non-shrinking recovery.

Fig. 4: A sample implementation of fault injection.

V. EVALUATION

We implement all the three fault tolerance designs in the MATCH workloads. Each design is run on three input problem sizes with the default scaling size (64 processes) with and without fault injection. Each design is also executed on four scaling sizes (64 processes on 32 nodes, 128 processes on 32 nodes, 256 processes on 32 nodes, and 512 processes on...
C. Performance Comparison on Different Scaling Sizes

In this experiment, we run each evaluation on four scaling sizes with the default input problem size (small). We seek to compare the scaling efficiency of the three fault tolerance designs with and without process failures.

**Without A Failure:** Figure 5 shows the average execution time with no failure. We break down the execution time to the application execution time and the time to write checkpoints.

Overall, we can see that among the three fault tolerance designs, ULFM-FTI performs worst. RESTART-FTI and REINIT-FTI perform similar and better than ULFM-FTI.

We first observe that FTI checkpointing scales well. The time spent on writing checkpoints modestly increases with more processes. This implies that there are a number of collective operations used in FTI L1 checkpointing. The time for writing checkpoints is accounted for 13% of the total execution time.

Second, we observe that Reinit has no impact on application execution when there is no failure. We use the FTI application execution time as the baseline for comparison because FTI is an application-level checkpointing library, whereas ULFM and Reinit modify the MPI runtime. We can see that the application execution time of REINIT-FTI is very close to the application execution time of RESTART-FTI. However, ULFM-FTI introduces overhead to the application execution. This overhead grows as the number of processes goes up. This is understandable. ULFM is implemented across MPI runtime and application levels. It can introduce memory access and communication latency to the application execution and further affect the application execution efficiency. As reported in a ULFM paper [24], ULFM implements a constantly heartbeat mechanism for failures detection, and also amends MPI communication interfaces for failure recovery operations. These changes must have an impact on application execution.
efficiency. Different from ULFM, Reinit incurs overhead only when a failure happens because it does not perform any background operation during application execution.

Furthermore, we observe that the times for writing checkpoints in RESTART-FTI and REINIT-FTI cases are close. This indicates that Reinit has no interference on FTI checkpointing, yet ULFM has a small impact on FTI checkpointing in cases such as HPCCG and miniVite. This is reasonable. Reinit is implemented at the MPI runtime level, which has a minimal impact on application-level operations, where the FTI operations run. In contrast, ULFM does a significant amount of collective operations for a periodic heartbeat in the MPI runtime, which leads to background overhead.

**With A Failure:** Figure 6 shows the breakdown of execution time recovering from a process failure in different scaling sizes. Figure 7 shows the MPI recovery time for different scaling sizes.
Overall, we observe that REINIT-FTI achieves the best performance compared to RESTART-FTI and ULFM-FTI. There are two reasons. First, Reinit recovery does not affect application execution, including checkpoint writing. Second, Reinit recovery uses the least time for MPI recovery than restarting and ULFM recovery. Those are similar observations derived from Figure 5. Furthermore, we provide new observations by comparing the MPI recovery efficiency for the three fault tolerance designs.

**ULFM recovery vs. Reinit Recovery.** We find that ULFM recovery time can be up to 13 times larger than Reinit recovery time, and four times larger on average. We can also see a trend that the ULFM recovery time increases as the number of processes grows, thus not scaling well. Different from ULFM, we find that Reinit recovery is independent of the number of processes. Since, ULFM enforces a variety of fault tolerance collective operations on all MPI processes to enable MPI global non-shrinking recovery. Even worse, ULFM implements these fault tolerance operations at the application level, which needs to synchronize with other fault tolerance operations implemented at the MPI runtime. By contrast, Reinit is implemented at the MPI runtime level, and Reinit requires...
much fewer collective operations.

**Restart vs. Reinit recovery.** We find that the restart recovery can be up to 22 times slower than Reinit recovery, and 16 times slower on average. This is expected. Redeployment of the MPI setup and allocation of resources for restarting the execution is very expensive. Reinit recovery repairs MPI state online.

**Restart vs. ULFM recovery.** Restart recovery is 2 to 3 times slower than ULFM recovery. Similarly to Reinit, ULFM recovery is online, which is much more efficient than redeployment.

**D. Performance Comparison on Different Input Sizes**

In this experiment, we compare the performance efficiency of the three fault tolerance designs on three input problem sizes with the default scaling size (64 processes), with and without fault injection.

**Without A Failure:** Figure 8 shows the execution time breakdown in a process failure in different input problem sizes. Note that we omit the time of reading checkpoints because it is in the order of milliseconds. Also, Figure 10 shows the recovery time for different input problem sizes.

The same observations from Figure 8 and the scaling experiments still hold. The new observation is that the recovery time of either ULFM or Reinit negligibly changes for different input problem sizes. This is an interesting finding but follows from their operation. When a failure occurs, ULFM starts collecting messages among daemons and processes in the background, while the program execution terminates. ULFM recovery dominates the execution. Reinit is fully implemented in the MPI runtime, which is even more difficult to be affected. We conclude that ULFM and Reinit recovery are independent of the input problem size.

**Conclusion.** (1) ULFM delays application execution, whereas Reinit has a negligible impact on the application execution; (2) ULFM affects the performance of FTI checkpointing, whereas Reinit has a negligible effect on it; (3) Reinit performs better than ULFM both when there is no failure and when there is a failure for MPI global, backward, non-shrinking recovery; (4) REINIT-FTI is the most efficient design within the three fault tolerance designs for MPI global, backward, non-shrinking recovery.
E. Use of MATCH

MATCH can help HPC programmers aiming at MPI fault tolerance in three ways. (1) We provide hands-on instructions of implementing ULFM with FTI, Reinit with FTI, and FTI with Restart on representative HPC proxy applications. MATCH is open-source. Programmers can learn with less effort on how to implement the three fault tolerance designs to an HPC application through the MATCH code. (2) We provide a data dependency analysis tool to identify data objects for checkpointing. Those data objects are the minimal data objects needed to guarantee the application execution correctness after restoring the application state. This is especially useful for applications with many data objects that need to be checkpointed. (3) MATCH can also be a foundation for future MPI fault tolerance designs. Programmers can develop new MPI fault tolerance designs on top of the three fault tolerance designs. For example, the ULFM global non-shrinking recovery can be replaced with the ULFM local forward recovery; the FTI checkpointing can be replaced with the SCR checkpointing. This is also part of our future work. Lastly, we encourage programmers to add new HPC applications and new MPI fault tolerance designs to MATCH.

VI. RELATED WORK

Data Recovery. Checkpointing is the commonly used approach to restart an MPI application when a failure occurs. Hargrove et al. develop a system-level checkpointing library—the Berkeley Lab Checkpoint/Restart (BLCR) library—to run checkpointing at system-level using the Linux kernel. Furthermore, Adam et al. propose multi-level checkpointing aiming to significantly advance checkpointing efficiency. CRAFT provides a fault tolerance framework that integrates checkpointing to ULFM shrinking and non-shrinking recovery. In this work, we choose FTI for checkpointing for data recovery because of the high efficiency and its extensive documentation. We plan to integrate and evaluate more checkpointing mechanisms in addition to FTI in future work. Furthermore, different to existing work, we also provide a data dependency analytic tool to aid programmers in identifying data objects for checkpointing.

MPI Recovery. ULFM is a leading MPI recovery framework in progress with the MPI Fault Tolerance Working Group. ULFM provides new MPI interfaces to remove failed processes and add new processes to communicators, and to perform resilient agreement between processes. ULFM requests programmers to implement shrinking or non-shrinking recovery using these interfaces. ULFM provides flexibility to programmers, but there is significant learning effort before programmers can correctly use ULFM interfaces to implement ULFM recovery. A large body of work has explored and extended the applicability of ULFM. Teranishi et al. replace failed processes with spare processes to accelerate ULFM recovery. Bosilca et al. and Katti et al. propose a series of efficient fault detection mechanisms for ULFM.

Reinit is a more efficient solution for MPI global recovery. Reinit hides the MPI process recovery from programmers by implementing it in the MPI runtime. Reinit provides a simple interface to programmers to define a global restart point, in the form of a resilient target function. The early versions of Reinit have limited usage because they require hard-to-deploy changes to job schedulers. Most recently, Georgakoudis et al. propose a new design and implementation of Reinit into the Open MPI runtime.

Later, researchers realize the efficiency of combining checkpointing and MPI recovery for higher efficiency of MPI fault tolerance. For example, FENIX and CRAFT both design and develop a checkpointing interface that supports data recovery for ULFM shrinking and non-shrinking recovery. However, developers must explicitly manage and redistribute the restored data among survivor processes in case of a non-shrinking recovery. This can easily cause load imbalance problems. Also, they only evaluate their frameworks on two applications, and do not compare their fault tolerance frameworks to other fault tolerance designs. In conclusion, there is no existing work that either benchmarks the design and implementation of MPI fault tolerance, or compares the performance efficiency of different fault tolerance designs. Different from FENIX and CRAFT, we evaluate and comprehensively compare fault tolerance designs that combine FTI checkpointing and MPI recovery frameworks (ULFM and Reinit) on a collection of HPC proxy applications.

MPI Fault Tolerance Benchmarking. There have been many benchmark suites developed for MPI performance modeling. SKaMPI is an early benchmark suite that evaluates different implementations of MPI. Bureddy et al. develop a benchmark suite to evaluate point-to-point, multi-pair, and collective MPI communication on GPU clusters. However, there is no MPI benchmark suite that focuses on fault tolerance and evaluates fault tolerance designs in MPI. This paper proposes a benchmark suite MATCH for benchmarking MPI fault tolerance.

VII. CONCLUSIONS

MPI fault tolerance is becoming an increasingly critical problem as supercomputers continue to grow in size. We have designed and implemented a benchmark suite, called MATCH, to evaluate MPI fault tolerance approaches. Our benchmark suite has six representative HPC proxy applications selected from existing, flagship HPC benchmark suites. We comprehensively evaluate and compare the performance efficiency of three different fault-tolerance designs, implemented on the selected applications. The evaluation results reveal that FTI checkpointing with Reinit recovery is the most efficient fault tolerance design of those three. Our analysis and finding provide significant insight to HPC developers on MPI fault tolerance.

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