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GeoInv3D: A Scalable Forward Modeling Framework for Full Waveform Inversion Problem

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SUMMARY

Full Waveform Inversion is a high-resolution imaging method that has raised considerable interest in the oil industry since a decade. It has been mainly used as a P-wave velocity modeling building tool, while extension to multi-parameter elastic anisotropic reconstruction is now an active field of research. In this context, designing computationally-efficient and versatile FWI softwares, in which different numerical schemes for seismic modeling, wave physics and optimization algorithms can be interfaced easily, is of crucial interest. In this study we describe an object oriented framework based on the definition of abstract interfaces of components involved in frequency or time domain FWI workflow. We point out the numerical modeling of the full seismic wavefield as the central component and that the proposed design is suitable to interface different modeling approaches involving different discretisations and physics with the optimization kernel. Then we demonstrate the capability of the framework to preserve parallel scalability and efficiency of kernels even in an object oriented programming context. Lastly we present a concrete realisation of this abstract framework via an application of an acoustic 3D time-domain FWI on the Valhall field using a staggered grid finite difference scheme.

Introduction

Full Waveform Inversion (FWI) is an appealing technique to retrieve quantitative high-resolution models of the subsurface (see Virieux and Operto, 2009, for a review). FWI relies on a local optimization problem that aims to minimise differences between observed and simulated seismic data. The misfit function can be formulated either in the time-domain or in the frequency-domain. A necessary ingredient to perform local optimization is the gradient of the misfit function, estimated efficiently by an adjoint technique (Plessix, 2006). This gradient involves the solution of two forward seismic simulations: one for the incident wavefield and one for the back-propagated adjoint wavefield.

When considering time-domain modeling, we can view to perform inversion in the time domain or in the frequency domain after transforming on the fly the time-domain wavefields in the frequency domain by discrete Fourier transform (Sirgue et al., 2007).

In this study we present an object oriented framework that is suitable to interface different modeling approaches involving different discretisations and physics with the optimization kernel. We will finally illustrate the performance of this framework with a real 3D FWI application on the Valhall field.

Theory

We first start from the time-domain wave-equation written in the generic form

$$\partial_t \mathbf{u}(\mathbf{x},t) - N(\mathbf{m}(\mathbf{x}))H(\nabla)\mathbf{u}(\mathbf{x},t) = \mathbf{s}(\mathbf{x},t), \tag{1}$$

where $\mathbf{u}(\mathbf{x},t)$ is the wavefield formed by particle velocity and stress components. The operator $N(\mathbf{m})$ depends on physical properties only and $H(\nabla)$ is related to spatial derivatives. This expression, coming from Burridge (1996), allows to write the wave-equation as a first-order (implicit) symmetric hyperbolic system even for general anisotropic media, which is quite appealing to derive adjoint formulation as the forward operator is self-adjoint :

$$N^{-1}(\mathbf{m}(\mathbf{x}))\partial_t \mathbf{u}(\mathbf{x},t) - H(\nabla)\mathbf{u}(\mathbf{x},t) = N^{-1}(\mathbf{m}(\mathbf{x}))\mathbf{s}(\mathbf{x},t). \tag{2}$$

We can then naturally derive the time-domain FWI gradient expression as

$$\mathscr{G}(\mathbf{x}) = \int_T dt \lambda^T(\mathbf{x},t)\frac{\partial N^{-1}(\mathbf{m}(\mathbf{x}))}{\partial \mathbf{m}}\partial_t \mathbf{u}(\mathbf{x},t), \tag{3}$$

where $\lambda(\mathbf{x},t)$ is the adjoint wavefield which satisfies a similar equation than 1 with a specific source term.

Assuming the simulation of both $\mathbf{u}(\mathbf{x},t)$ and $\lambda(\mathbf{x},t)$ have reached the steady state, we can compute their Fourier transform, leading to the frequency-domain solution $\mathbf{u}(\mathbf{x},\omega) = \mathscr{F}_\omega \mathbf{u}(\mathbf{x},t)$ and $\lambda(\mathbf{x},\omega) = \mathscr{F}_\omega \lambda(\mathbf{x},t)$, where $\mathscr{F}_\omega$ is the Fourier operator to extract frequency ω. Considering these frequency-domain solutions available, we can rely on a frequency-domain FWI gradient, which is equivalent to equation (3) if steady-state has been reached :

$$\mathscr{G}(\mathbf{x}) = \sum_\omega -i\omega\lambda^T(\mathbf{x},\omega)\frac{\partial N^{-1}(\mathbf{m}(\mathbf{x}))}{\partial \mathbf{m}}\mathbf{u}(\mathbf{x},\omega). \tag{4}$$

Algorithms

Time-domain FWI gradient

Equation (3) requires multiplying the incident and adjoint fields at each time step. As the adjoint field relies on a final time condition, the adjoint simulation is generally recast as an initial time problem

Algorithm 1 Algorithm of the time-domain gradient computation

for $it = 1$ to nt **do**
  update incident field $\mathbf{u}(\mathbf{x},t)$ in forward time + store (in memory) fields on boundaries
  extract solution at receivers
end for
Misfit function and residuals computations
for $it = 1$ to nt **do**
  compute the adjoint source term
  update adjoint field $\lambda(\mathbf{x},t)$ in forward time
  restore fields on boundaries + update incident field $\mathbf{u}(\mathbf{x},t)$ in backward time
  update the gradient
end for

Algorithm 2 Algorithm of the frequency-domain gradient computation.

for $it = 1$ to $nt2$ **do**
  update incident field $\mathbf{u}(\mathbf{x},t)$ in forward time
  update the frequency domain incident field $\mathbf{u}(\mathbf{x},\omega)$ for frequencies of interest
  extract solution at receivers
end for
Misfit function and residuals computations
for $it = 1$ to $nt2$ **do**
  compute the adjoint source term
  update incident field $\lambda(\mathbf{x},t)$ in forward time
  update the frequency-domain adjoint field $\lambda(\mathbf{x},\omega)$ for frequencies of interest
end for
compute the gradient for each frequency and summation

through a change of variable with respect to time. However, this implies that gradient requires fields at time steps that are not computed simultaneously. Three strategies can be used to overcome this issue:

(1) Store the whole incident wavefield on disks when it is computed, to be able to read it at the time of adjoint computation. This strategy allows to model viscous media, does not require re-computation of wavefield, but requires intensive I/Os for large size data volume.

(2) Store partially the incident wavefield in memory at specified time steps through a check-pointing strategy (Symes, 2007; Anderson et al., 2012), and recompute the missing time-steps when required at the time of adjoint computation. This strategy allows to model viscous media but requires some re-computation of the incident wavefield (typically between 1 and 4 times).

(3) Store the incident wavefield on the boundaries of the computational domain at all time steps when it is computed and the final time field. When computing the adjoint field, recompute the incident field backward in time from the final step and the boundaries. This strategy does not allow to simulate viscous media (as it assumes reversible equation) but requires only one re-computation of the incident field.

Algorithm 1 shows the required steps to compute the time-domain gradient with the third strategy.

Frequency-domain FWI gradient

The frequency-domain gradient implementation appears simpler to compute (algorithm 2), as soon as the frequency-domain wave-equation solutions are available. One incident wavefield computation is saved, compared to time-domain formulation, but the Fourier transform is required based on discrete Fourier transform (Sirgue et al., 2007) or phase-sensitive detection (Nihei and Li, 2007).

Both algorithms highlight the numerical modeling of the seismic wavefield as the central component of the FWI.

Framework architecture

After the identification of use and reuse of the forward modeling kernels in adjoint modeling within both time and frequency-domain FWI formulations, we define a component-based framework dedicated to FWI. The aim is not only to integrate the different approaches in a single tool, but also to share common services between them and to support adding new ones.

Figure 1 describes abstract components involved in the FWI workflow. This independence with the internal representation is the key point of our proposal for construction of FWI applications. The framework is interfaced with two libraries developed by the SEISCOPE project: an optimization toolbox and a 3D domain decomposition library. The optimization toolbox implements a variety of gradient-based optimization algorithms such as steepest-descent, nonlinear conjugate-gradient and Newton based methods (quasi-Newton LBFGS and Truncated-Newton) and is based on a reverse communication interface. The 3D domain decomposition library manages two nested levels of MPI parallelism: one for shot distribution and one for the domain decomposition.

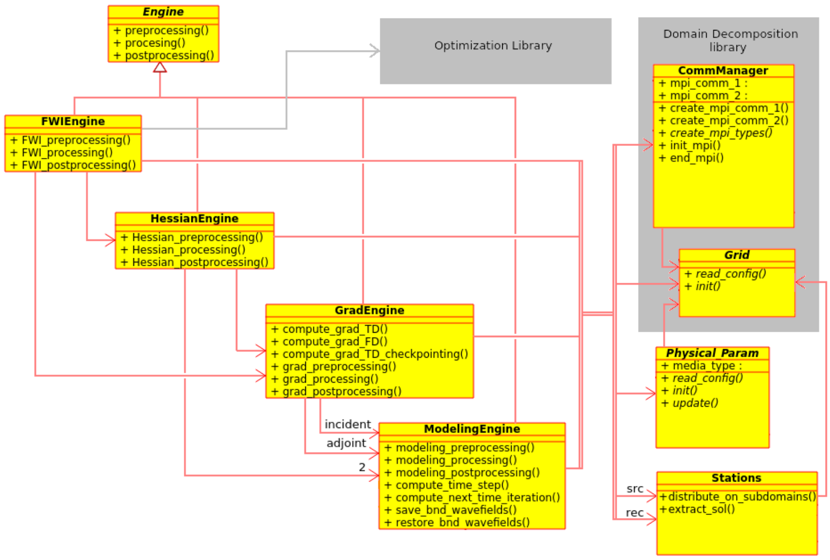

Figure 1 *Representation of the abstract level of the framework architecture. It shows all high-level components defined in the framework and the relation between each of them. Yellow boxes define component, vertical arrows inheritance and horizontal ones the relations between the components. The main component is the engine. By inheritance, it can be in fact a modeling, a gradient, an Hessian or a FWI engine. The other abstract components are: the grid to manage structured and unstructured grids, the communication manager through domain decomposition and shot distribution, the physical parameters managing media properties and stations identifying sources and receivers. The gradient engine needs two modeling engine components to compute the gradient: one for the incident field and one for the adjoint field. The implementation can perform gradient computation in time or frequency domain and include check-pointing functionality when needed (for non reversible viscous system). The FWI engine coupled with the optimization library will drive the gradient computation.*

Figure 2 shows specialisation of the modeling engine abstract component within staggered grid finite difference schemes for acoustic or elastic wave propagation in isotropic or anisotropic VTI media.

The framework is implemented in Fortran 2003 following object oriented programming (OOP) concepts. Yet, object-oriented systems offer a great deal of value to the development of scientific software. The problem is how to incorporate them into the standard ways of programming scientific software to gain the flexibility they promise, but without losing the performance that we want. From our experience, performance stands in the efficient implementation of the kernel of the modeling. The overhead involved by OOP is practically eliminated if polymorphic classes are only defined at high level (to switch between different applications, discretisations, physic,...) and not at low level.

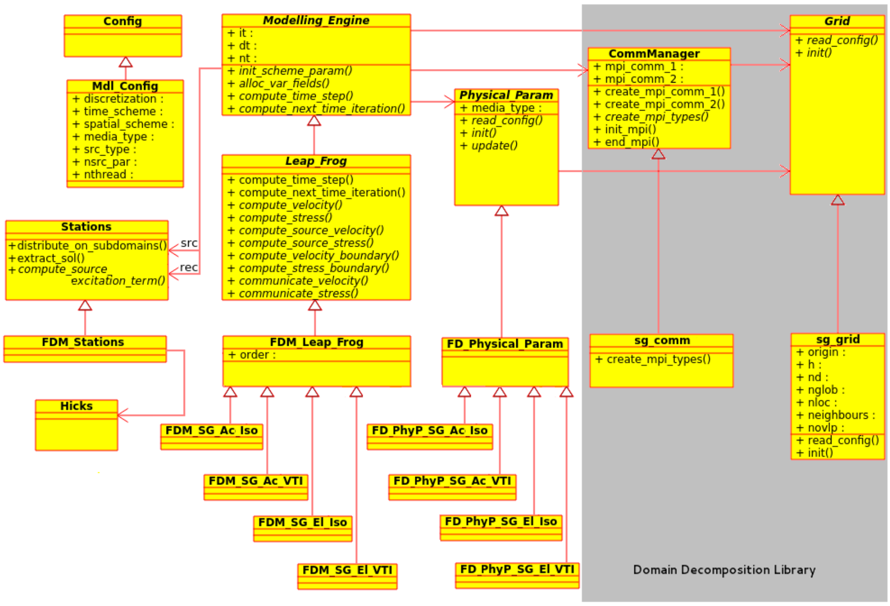

Figure 2 *All the components who need specific implementation for finite difference are derived to create a most specific component and the methods are overridden. The communication manager and the grid have their own implementation for FDM that are encapsulated in the domain decomposition library.*

Conclusions

The design discussed in this study satisfies three main specifications: [i] the definition of a high-level component based architecture for a FWI framework, ensuring the independence with the internal representation of the different approaches; [ii] the reuse of modeling time step functions in incident and adjoint field modeling; [iii] the preservation of parallel scalability and efficiency of kernels.

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